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MUSCULOSKELETAL LOADING AND ADAPTATION IN NOVICE RUNNERS

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ABSTRACT

Running is a practical, affordable and efficient way to become physically active. Running programs for absolute beginners, taking novice runners from one to thirty minutes of continuous running, are therefore very popular. Although these programs are effective in increasing cardiorespiratory fitness and endurance, the effect of a running program for beginners on the musculoskeletal system is less well established. The mechanical loading during running causes stress and strains on the bones, tendons, ligaments and muscles of the lower limb. Biological tissues are responsive to mechanical loading. Therefore, it can be expected that, when following a running program for beginners, the musculoskeletal structures will adapt to the increased loading. Bones respond to increased mechanical loading by changes in structure, leading to hypertrophy of the bone parts that are under compression. In the long term, this leads to higher bone mass in people who engage regularly in weight-bearing exercise. Tendons respond to repeated loading by increases in thickness and stiffness. During running, the bones and tendons of the lower limb and in particular the tibia and the Achilles tendon, are loaded repeatedly. Therefore, the aim of this work was to determine the influence of a typical, 12 week running program for beginners on running kinematics and kinetics, tibial bone geometry and density, and Achilles tendon stiffness in novice runners. Understanding how loading during running leads to tissue adaptations contributes to understanding both training and injury mechanisms. This can eventually lead to the development of training programs that improve running performance while minimizing injury risk.

To study musculoskeletal adaptations following a 12 week running program for beginners, we recruited 71 physically inactive subjects to participate in a running program. Before and after the running program, running kinematics and kinetics were measured to calculate loading variables and to determine changes in running kinematics and kinetics after 12 weeks of training. A pQCT-scan of the lower leg was performed before and after the running program to determine the changes in tibial bone properties after 12 weeks of running. Achilles tendon stiffness was measured non-invasively to determine the influence of the running program on Achilles tendon stiffness.

ADAPTATION OF RUNNING KINEMATICS AND KINETICS

Running kinematics influence the way that forces are distributed over the different structures in the body. Because of this relationship between running biomechanics and structure loading, several previous studies have identified biomechanical risk factors for developing overuse injuries. These risk factors include increased hip and knee internal rotation and adduction, increased ankle pronation, and higher loading rate (the slope of the vertical ground reaction force curve during impact). At the same time, running kinematics and kinetics influence running performance. In previous studies, several biomechanical factors have been related to better running economy, such as lower vertical oscillation of the centre of mass, greater leg stiffness, less leg extension at toe-off, and lower braking forces. Intuitively, there are clear relationships between running style (kinematics and kinetics) and injury risk and running economy. Well trained runners are more economical compared to novice runners. In addition, incidence of overuse injuries is higher in novice runners compared to well trained runners. We hypothesized therefore that training would lead to adaptations in running kinematics and kinetics that have previously been associated with lower injury risk and better running economy.

Overground running kinematics and kinetics were measured in 27 runners before and after the running program using motion capture and a force platform. Results showed almost no changes in running kinematics and kinetics after the training program. The only significant differences were an increase in peak hip external rotation moment from 0.02 (SD: 0.02) Nm/kg to 0.03 (SD: 0.02) Nm/kg and a decrease in peak vertical ground reaction force from 23.1 (SD: 1.9 N/kg) to 22.2 (SD: 1.8 N/kg). This indicates that following a 12 week running program for beginners does not lead to changes in running kinematics or kinetics that have been associated with better running economy or injury risk.

ADAPTATION OF THE TIBIA

We evaluated the influence of a 12 week running program for beginners on tibial bone properties. High bone mass is associated with weight-bearing exercise and is considered a positive adaptation since it protects against bone injuries. However, it is unclear whether endurance running provides sufficient mechanical loading to provoke an osteogenic response. We measured bone geometry and density of the tibia using peripheral quantitative computed tomography (pQCT) in 11 female novice runners before and after following a 12 week running program. pQCT results revealed small increases in bone mass and area at the distal tibia. Loading rate during running was positively related to increase in bone mass at the distal tibia, indicating that higher frequency loading on the tibia during running is associated with larger bone adaptations. However, since these high loading rates have been identified in the past as a risk factor for developing overuse injuries to the tibia, there is a fine line between tibia loading and overloading.

ADAPTATION OF THE ACHILLES TENDON

Achilles tendon stiffness, or the ability of the Achilles tendon to resist change in length when pulled on by a given force, usually increases with training and decreases with inactivity. However, the specific effect of running on Achilles tendon stiffness is not well known. We measured Achilles tendon stiffness before and after the running program in 22 novice runners by measuring tendon length change using ultrasound during a maximal isometric contraction. Results showed no significant increase in Achilles tendon stiffness after the running program. Therefore, endurance running may not provide high enough tendon strains to yield increases in tendon stiffness, or the Achilles tendon takes longer than 12 weeks to adapt to the loads imposed on the tendon by the running program.

RUNNING KINEMATICS AND FATIGUE

Runners will often get fatigued during a training session. Previous studies have shown that several kinematic variables that are considered risk factors for the development of overuse injuries, increase with fatigue. Therefore, we aimed to determine the influence of fatigue on running kinematics. We hypothesized that novice runners show larger changes in kinematics during an exhaustive run compared to well trained, competitive long distance runners, who may cope better with fatigue during a training session. Therefore, we used a cross-sectional study design to compare running kinematics during an exhaustive run on a treadmill between 15 novice runners and 15 well-trained, competitive long-distance runners.

Results showed that there were changes in running kinematics after the exhaustive run: pelvic anterior tilt and pelvic rotation range of motion increased in both groups. Novice runners also showed a significant increase in forward trunk lean over the course of the run. This confirms that untrained runners are more susceptible to changes in running kinematics with fatigue than trained runners. However, these differences are, to our knowledge, not related to injury risk, although this needs further exploration.

CONCLUSION

In conclusion, we can state that although 12 weeks of running improved the distance participants were able to run, it did not lead to substantial changes in preferred running speed, running kinematics or running kinetics. Therefore, although there are differences in running kinematics between well-trained and untrained runners, there

are no indications that novice runners will improve their running technique over the course of 12 weeks. Also, the lack of changes in running kinematics and kinetics indicate that the loading per step during running does not change and therefore that loading during the running program increased proportionally with the number of steps. Early indications of increase in bone mass of the distal tibia were found in female participants, which indicates that running can lead to increased bone strength. Achilles tendon stiffness did not change, indicating that the 12 weeks of Achilles tendon loading during the running program was not sufficient to yield adaptations in tendon stiffness. Despite the limited adaptations in bone and tendon properties, injury incidence amongst our participants was low in comparison to other training programs, indicating that this program was well balanced in terms of musculoskeletal loading and adaptation.

SAMENVATTING

Hardlopen is een praktische, efficiënte en goedkope vorm van fysieke activiteit. Trainingsprogramma's voor absolute beginners zijn daarom erg populair. In deze programma's wordt wandelen doorgaans afgewisseld met hardlopen, waarbij de hardloopduur wordt opgebouwd naar 30 minuten over een periode van 12 weken. Eerdere studies hebben aangetoond dat deze programma's goed werken voor het verbeteren van het cardiorespiratoire systeem en het uithoudingsvermogen. Echter, het effect van hardlopen op het musculoskeletale systeem is minder goed bekend. Hardlopen geeft mechanische belasting op de botten, pezen, spieren en ligamenten van de benen. In normale omstandigheden reageren biologische weefsels op de krachten waaraan ze worden onderworpen door middel van structurele aanpassingen. Daarom kan men verwachten dat musculoskeletale structuren zich aanpassen aan de toenemende belasting die door het hardlopen wordt veroorzaakt. Botten reageren op toenemende belasting met hypertrofie op de plaatsen die samengedrukt worden. Op lange termijn kan dit leiden tot een toename in botmassa bij mensen die regelmatig aan lichaamsbeweging doen waarbij er krachten op de botten komen. Pezen reageren op een toename in belasting met een toename in dikte en stijfheid. Tijdens het hardlopen worden de botten en pezen in de onderbenen, met name de tibia (scheenbeen) en de Achillespees, bij iedere stap belast. Het doel van deze thesis is om het effect van een 12 weken durend hardloopprogramma voor beginners op de loopbeweging en op de mechanische eigenschappen van de tibia en de Achillespees te onderzoeken. Kennis over de relatie tussen belasting tijdens hardlopen en adaptatie van deze structuren draagt bij tot een beter begrip van trainingsmechanismen en het ontstaan van overbelastingsletsels. Dit kan uiteindelijk helpen bij het ontwikkelen van trainingsprogramma's die de hardloopprestaties verbeteren, terwijl het risico op blessures geminimaliseerd wordt.

Om aanpassingen na een standaard loopprogramma voor beginners te onderzoeken, rekruteerden we 71 inactieve proefpersonen om mee te doen aan een trainingsprogramma van 12 weken. Voorafgaand aan en na afloop van het loopprogramma werd een aantal metingen uitgevoerd om parameters gerelateerd aan belasting tijdens het hardlopen en aan mechanische eigenschappen van de tibia en de Achillespees te berekenen. De beweging van een loper (loopstijl) drukken we uit in gewrichtshoeken (kinematica) en in krachten en momenten (kinetica). De kinematica en kinetica tijdens het lopen werden gemeten door middel van een driedimensionale bewegingsanalyse en het meten van grondreactiekrachten. Hiermee kon worden bepaald of de loopstijl veranderde na het volgen van het loopprogramma. Ook konden er parameters worden berekend die gerelateerd zijn aan de belasting van verschillende structuren tijdens het lopen. Er werd een pQCT scan van het onderbeen gemaakt om de diameter en densiteit van de tibia vóór en na het loopprogramma te berekenen. Tenslotte werd de stijfheid van de Achillespees gemeten op een niet-invasieve manier met behulp van echografie.

AANPASSING VAN KINEMATICA

De kinematica beïnvloeden hoe de krachten die tijdens het lopen op het lichaam komen worden verdeeld over de verschillende structuren. Omdat er een relatie is tussen loopstijl en belasting, zijn er in het verleden verschillende studies gedaan die risicofactoren voor het ontwikkelen van overbelastingsletsels hebben geïdentificeerd. Deze risicofactoren bestaan uit de grootte van de schok tijdens het landen, het naar binnen bewegen (adductie) en naar binnen draaien (endorotatie) van de heup en de knie tijdens de steunfase en het naar binnen kantelen van de enkel (pronatie) tijdens de steunfase. Loopstijl beïnvloedt niet alleen de kans om geblesseerd te raken, het beïnvloedt ook hoe efficiënt iemand loopt. Een kleinere verticale amplitude van het lichaamszwaartepunt, een stijvere knie, heup en enkel tijdens de landing, minder strekking van het been bij de afzet en minder grote afremmingskrachten leiden tot een efficiëntere loopstijl. Goed getrainde lopers zijn efficiënter dan ongetrainde lopers. Daarom is onze eerste hypothese dat training leidt tot een toename van de variabelen die zijn gerelateerd aan een efficiëntere loopstijl en een afname van de variabelen die gerelateerd zijn aan het ontwikkelen van blessures.

Om deze hypothese te onderzoeken maten we kinematica en kinetica tijdens het lopen bij 27 beginnende lopers, vóór en na het volgen van een trainingsprogramma van 12 weken. Er waren weinig verschillen in de kinematica en kinetica na het volgen van het trainingsprogramma. De enige significante verschillen waren een toename van het exorotatiemoment in de heup en een afname van de piek van de verticale grondreactiekracht. Hieruit kan geconcludeerd worden dat een loopprogramma van 12 weken niet leidt tot veranderingen in loopstijl die geassocieerd zijn met risico op overbelastingsletsels of loopefficiëntie.

AANPASSINGEN VAN DE TIBIA

Ten tweede onderzochten we de invloed van een loopprogramma voor beginners op eigenschappen van de tibia. Fysieke activiteit waarbij krachten op de botten uitgeoefend worden kan leiden tot een toename in botmassa, mits de krachten niet zó hoog zijn dat ze directe schade aan de botten veroorzaken en mits er voldoende hersteltijd is tussen de trainingssessies. Een toename in botmassa is een gunstige aanpassing, omdat een hoge botmassa beschermt tegen botletsels, zoals fracturen bij vallen en stressfracturen. Het is echter niet bekend of 12 weken hardlopen voldoende belasting geeft om dit osteogene effect te bereiken. Om dit te onderzoeken maten we botdensiteit, botmassa en botomvang met behulp van peripheral quantitative tomography (pQCT) bij 11 beginnende, vrouwelijke lopers vóór en na het trainingsprogramma. De botscans lieten een lichte toename van botmassa aan het distale uiteinde van de tibia zien. De grootte van de schokken op het lichaam tijdens de landing bij het lopen was positief gerelateerd aan toename in botmassa ter hoogte van de distale tibia. Dit suggereert dat grotere schokken bij het lopen gunstig zijn voor botontwikkeling. In andere studies zijn deze schokken echter geïdentificeerd als risicofactor voor overbelastingsletsels. Er is dus blijkbaar een smalle grens tussen belasting en overbelasting van de tibia.

AANPASSING VAN DE ACHILLESPEES

Achillespeesstijfheid, ofwel de mate waarin de pees zijn lengte behoudt wanneer er met een bepaalde kracht aan getrokken wordt, neemt doorgaans toe bij belasting en af bij inactiviteit. Achillespeesstijfheid werd bij 22 deelnemers vóór en na het loopprogramma gemeten. Hiervoor maten we de hoeveelheid rek van de pees met behulp van echografie tijdens een maximale isometrische contractie van de kuitspieren. Resultaten wezen uit dat er geen significante toename van Achillespeesstijfheid optrad na het loopprogramma. Belasting van de Achillespees tijdens dit loopprogramma was dus waarschijnlijk te laag, of de trainingsduur van 12 weken was te kort om voor aanpassingen in peesstijfheid te zorgen.

LOOPSTIJL EN VERMOEIDHEID

Lopers raken vaak vermoeid tijdens een trainingssessie. Eerdere studies hebben aangetoond dat verschillende kinematische variabelen die risicofactoren zijn voor het ontwikkelen van overbelastingsletsels, toenemen met vermoeidheid. Daarom wilden we de invloed van vermoeidheid op de kinematica van het hardlopen onderzoeken. Onze hypothese hierbij was dat beginnende lopers grotere veranderingen in kinematica zouden hebben bij vermoeidheid, vergeleken met goed getrainde, competitieve lange-afstandslopers. Goed getrainde lopers zijn immers geoefend in het omgaan met vermoeidheid. Om te kijken of goed getrainde lopers anders reageren op vermoeidheid, lieten we 15 beginnende lopers en 15 wedstrijdlopers op een loopband lopen aan een uitdagend tempo totdat ze uitgeput waren. Onder invloed van vermoeidheid gingen de lopers anders lopen: aan het einde van de test was er een grotere voorwaartse kanteling en meer rotatie van het bekken in beide groepen. De onervaren lopers gingen daarnaast meer voorover leunen met hun romp als ze vermoeid raakten. Deze aanpassingen komen waarschijnlijk door vermoeidheid in de heup- en rompspieren. Ongetrainde lopers laten dus inderdaad grotere veranderingen in loopstijl zien als ze vermoeid raken. De variabelen die veranderden zijn echter tot nu toe niet geassocieerd met overbelastingsletsels of loopefficiëntie.

CONCLUSIE

Samenvattend kunnen we concluderen dat 12 weken hardlooptraining wel zorgt voor toename van het uithoudingsvermogen, maar niet veel effect heeft op de loopsnelheid en de loopstijl. Hoewel er een verschil is in loopstijl tussen goed getrainde en beginnende lopers, is 12 weken trainen niet voldoende om verschillen in loopstijl te zien. De bevinding dat er geen veranderingen zijn in de kinematica en kinetica na 12 weken trainen toont ook aan dat de belasting per stap niet verandert. Daarom zal de belasting van de verschillende structuren in het lichaam tijdens een loopprogramma proportioneel stijgen met het aantal stappen dat tijdens een training wordt gezet. We vonden lichte aanpassingen in de botmassa van de distale tibia bij de vrouwelijke deelnemers, wat aantoont dat hardlopen een goede manier kan zijn om de botmassa te vergroten. Achillespeesstijfheid nam niet significant toe, wat betekent dat 12 weken hardlopen niet voldoende belasting op de Achillespezen geeft om tot aanpassingen te leiden. Ondanks de minimale aanpassingen in de tibia en Achillespees was het aantal loopblessures in onze proefgroep laag in vergelijking met andere studies, wat erop wijst dat er weinig sprake was van overbelasting. Tenslotte tonen de resultaten van de laatste studie aan dat er bij het beoordelen van de loopstijl rekening moet worden gehouden dat deze verandert als de loper vermoeid raakt, met name bij beginnende lopers.

CHAPTER 1: GENERAL INTRODUCTION

BACKGROUND

Running is a form of exercise that has gained immense popularity over the last decades. Since the 1960's, running evolved from a mostly competitive sport practiced by few elite runners up to one of the most popular recreational sporting activities today. In 2009, it was estimated that Europe counts 50 million runners. Of the total population in Flanders aged 12-75 years, 19.2% was active in running.[1] Running is an economical way of exercising, since it is low in cost and can be done anywhere at any time. Running clubs often offer training programs for absolute beginners, but such programs are also freely available online. A typical training program for novice runners prescribes alternated walking and running intervals, with the running distance increasing each week. These programs typically exist of three training sessions per week, leading to 5000m or 30 minutes of continuous running over a 12-week period. The popularity of these running programs and the potential health benefits associated with exercise have led to a substantial body of literature on the population of novice runners.

Previous studies have shown that running programs for beginners are effective in increasing participants' cardiovascular health and maximal oxygen uptake.[2,3] A meta-analysis on the effects of habitual running on several indices of health in physically inactive adults showed that after 12 weeks there is already a reduction in body fat, in resting heart rate and triglycerides and an increased maximal oxygen uptake (VO_2max)[3]. These are obviously positive adaptations, showing that only 12 weeks of running training is already associated with health benefits. However, running programs for beginners have also been associated with high incidences of overuse injuries. Yearly overuse injury incidences of 20-70% have been reported in recreational runners, depending on the population and the definition of injury.[4] A recent review on injury incidence in different types of runners indicated that injury risk is even higher in novice runners compared to more experienced runners.[5] In a recent study on novice runners following an 8 week training program, 40% of participants reported at least one running-related injury.[6] The beneficial effects of running on the cardiorespiratory system along with the high injury rates in novice runners suggest that the cardiorespiratory system generally adapts to the increased stress caused by the increased running distance, while the musculoskeletal adaptation lags behind, leading to overloading of the musculoskeletal system. Besides causing increased health care costs, running injuries also lead to temporary or permanent discontinuation of physical activity and motivation loss, especially in novice runners. The most frequently developed overuse injuries in runners are medial tibial stress syndrome (MTSS) and Achilles tendinopathy.[7]

The large amount of studies on overuse injuries in runners shows that a lot of attention has been paid to running injuries due to maladaptation of structures when subjected to repeated loading. Maladaptation can occur when structures are loaded repeatedly, without allowing sufficient recovery time in between training sessions.[8] The microdamage caused by this overloading can accumulate, leading to maladaptation of the musculoskeletal structures.[9,10] For tendons, which contains fibrils consisting of collagen molecules that are connected with crosslinks[11], mechanical loading results in an upregulation of collagen expression and increased collagen synthesis. However, collagen degradation also peaks after exercise. Over the first 24-36 hours after exercise, there is a net degradation of collagen, which shifts to a net synthesis 36-72 hours after exercise.[9] Therefore, when rest periods in between training sessions are consistently too short over a longer period of time, a gradual loss of collagen will occur, leading to degradation of the tendon.[9] For bones, mechanical loading causing bone strains can lead to microdamage, which initiate a bone remodelling response.[12] However, repeated loading without sufficient rest in between loading sessions can lead to accumulation of microdamage, resulting in stress fractures.[13]

However, far less is known about positive musculoskeletal adaptations in runners. Much like the cardiovascular system, the musculoskeletal system can adapt to the increased loading placed upon the system while running, as biological tissues are responsive to changes in mechanical loading. Tissues that transmit forces, such as muscle, tendon, ligament, cartilage and bone, remodel when subjected to increased mechanical loading.[8] Exercise, such as running, provides mechanical stimuli to the tissues by means of increased muscle and external forces. Given that the loading is repetitive in nature and below the tensile strength of the tissue and that there is sufficient recovery time between training sessions, tissue structures adapt their composition to accommodate to the new loading levels.[8] In contrast, inactivity reverses this process.[14] Most studies focusing on tissue adaptations to loading have investigated long-term (6 months and longer) effects rather than investigating the effects of current short-term training programs (typically 12 weeks). For this thesis, we will focus on the tissues of the tibial bone and the Achilles tendon, since these structures are repeatedly loaded during running[15,16] and are most likely to suffer from overloading and consequently overuse injury in the novice running population.[7]

Bone adaptation to running

Julius Wolff stated as early as 1870 that under mechanical loading, bones respond by bony apposition in the concavity but resorption in the convexity of the bone. This leads to a change in structure of the bone, with hypertrophy of the parts that are under compression.[17] In the long term, this results in higher bone mass in people who engage regularly in weight-bearing exercise. Higher bone mass is a positive adaptation, since it can prevent the major health problems caused by loss of bone mass associated with aging.[14,18]

Previous studies have associated bone remodelling with strain rate (deformation of the bone over time)[19], indicating that not only high forces, but also high impacts are necessary to cause changes in bone structure. Several cross-sectional studies demonstrated that runners have higher bone mineral density (BMD) compared to non-runners[20–24], indicating that the bone loading associated with running is sufficient to cause long-term bone adaptation. However, longitudinal studies on the effect of running on bone geometry and BMD are necessary to determine causal relationships. A small number of longitudinal studies examining the effect of a training intervention on bone geometry and BMD exists.[25–28] Snow-Harter et al found an increase in lumbar BMD after both 8 months of strength training and 8 months of jogging.[28] Bassey et al. found an increase in femoral BMD after 5 months of jumping exercise.[27] Helge et al. found an increase in tibial BMD after 14 weeks of football and running training.[25] Krustrup et al. found an increase in whole body BMD after 16 months of football training.[26] This literature suggests that weight-bearing exercise can cause bone loading that is high enough to yield adaptations in bone. However, it is unknown to what extent a typical 12-week running program causes changes in BMD.

Achilles tendon adaptation to running

The Achilles tendon forms the link between three different calf muscles and the foot, and is therefore responsible for transferring the forces from the calf muscles to the foot and vice versa. Tendons play an important role in the efficiency of locomotion since they can store and release elastic energy.[29] According to the Hill muscle-tendon model, a muscle-tendon unit (MTU) consists of a contractile element (the muscle fascicles), a series-elastic element (the tendon and the intrinsic elasticity of the myofilaments) and a parallel elastic element (formed by the connective tissues surrounding the contractile element), that is stretched whenever the muscle produces force.[30] The compliance of the tendon (the change in length when pulled on by a given force) determines how much energy can be stored during each step and how the muscle length changes during contractions.[31] A compliant tendon can store more elastic energy when stretched and allows the muscle fascicles to operate at a near constant length, despite length changes in the MTU. Thereby, the muscle fascicles can produce more force since they can operate at a more favourable muscle length.[32–34] On the other hand, when a tendon is too compliant, the muscle fascicles have to contract at a higher shortening velocity to stretch the tendon to longer lengths during force production, which is less efficient.[33] Therefore, there seems to be a tendon stiffness that is optimal for muscle efficiency during running. Studies of Lichtwark et al. show that indeed, there is an Achilles tendon stiffness that is optimal for muscle efficiency during running, which is speed-dependent.[33,35] In trained runners, higher tendon stiffness has been associated with better running economy.[36] This suggests that in running, efficient muscle work is favoured over energy storage and release[36,37] and that increased tendon stiffness is a positive adaptation.

During running, the Achilles tendon is loaded heavily, with forces up to 12.5 times body weight during each step.[15] Running causes repeated tendon loading, which can lead to tendon adaptations. However, it is unknown whether running causes sufficient tendon loading to induce tendon adaptations. Previous studies have shown increased size and stiffness with various types of training including strength and endurance training.[38–41] Specifically, in strength training studies it was shown that a training period of 3 months increased the stiffness of the Achilles tendon. On the other hand, detraining decreases tendon stiffness within the time course of 1 month.[42] This suggests that Achilles tendon stiffness and thickness are trainable, but it is still unclear whether endurance running stimulates tendon adaptations. Cross-sectional studies have found higher Achilles tendon cross-sectional area in runners versus non-runners[43–46], but differences in Achilles tendon stiffness have not been found[46–50]. The Achilles tendon is the most frequently injured tendon in the human body. Eight to 10 percent of participants in a three month running program suffer from Achilles tendon injury, indicating that Achilles tendons are easily overloaded during the initial training phase.[51,52] Therefore, we aimed to determine the adaptations in Achilles tendon stiffness after a typical, 12-week running program for beginners. A more elaborate introduction in Achilles tendon adaptation and injury in runners is provided in **a review article (chapter 4):** Achilles tendon adaptation and Achilles tendinopathy in runners.

Loading during running

In this work, musculoskeletal loading is defined as the forces and moments that are applied to the different musculoskeletal structures in the body. Loading during running can be quantified across scales. On a whole body level, ground reaction forces (GRF), the force that the ground imposes on the body during each step, can be measured.[53] At joint level, moments and forces can be estimated using an inverse dynamics approach. This approach uses GRF, kinematics and inertial properties of the body to calculate internal moments and forces generated by the muscles.[54] On an organ level, forces in joints, bones, tendons, muscles and ligaments are evaluated.

Direct measurement of these forces is complicated and invasive, but estimations can be made using musculoskeletal models.[55] Also, the cumulative load, or the cumulative forces over a period of time, such as the time span of a training session, are relevant when assessing musculoskeletal loading during running.[56] Various factors, including running kinematics and kinetics[57–59], surface[60], shoe type and tissue morphology[61,62] determine how the loads are distributed over the different structures, which may lead to individual differences in the way these structures will adapt to loading.

For this thesis, we focus on adaptations at organ level and more specifically on the Achilles tendon and the tibial bone. For the Achilles tendon, tendon strain magnitude i.e.: the change in tendon length in relation to a reference length – typically at rest, is proposed as the variable that is most related to tendon adaptation.[63] However, tendon strain, under influence of an applied force[64], is difficult to measure in vivo during activities like running. Previous studies have used buckle transducers, fibre optic sensors, and other implantable force probes that are placed in or around the mid-substance of the tendon (e.g. [65–67]). However, all of these methods are invasive and not applicable to monitor tendon loading during the course of a training program. Recent advances in ultrasonography and magnetic resonance imaging have allowed to non-invasively measure tendon strain in vivo, however only during slow movement and muscle contraction.[68] In addition, three-dimensional movement analysis in combination with the simultaneous measurement of GRF also provides insight in the loading of the tendon. Using inverse dynamics, the moment around the ankle (internal ankle plantar flexor moment) can be used as an approximation of tendon loading. This ankle plantar flexor moment is directly related to Achilles tendon force: Achilles tendon force has been calculated previously in a study by Lichtwark et al. by dividing ankle joint moment by the Achilles tendon moment arm. Using this method, Achilles tendon force will be slightly underestimated, since the ankle joint moment does not account for co-contraction of other muscles.[35] According to another study by Lichtwark et al.[69], where Achilles tendon strain was calculated using a combination of ultrasound measurements and musculoskeletal modelling, Achilles tendon strain peaks around 60% of stance phase, around the same time as maximal dorsiflexion angle occurs. This is also approximately the time instant at which peak ankle plantar flexor moment occurs. Therefore, the peak ankle plantar flexor moment should be a good indirect measure of tendon strains.

For the tibial bone, bone strains are proposed as the stimulus for adaptations.[19,70] As with tendon strain, direct measures of bone strain involve invasive measurements such as a strain gauge. To measure tibial bone loading non-invasively, GRF have been used in the past.[71] During running, bone strains are caused by a combination of muscle forces, GRF and forces imposed on the bone by passive structures (ligaments). In the distal bones of the lower limb, such as the tibia, a large proportion of the muscle forces are caused by the GRF, since gravitational loads require muscle activity to stabilize the skeleton[72] and due to the limited contribution of the inertial properties of the foot to the ankle joint moments.[73] Impact loading can be derived from the vertical GRF as the impact peak (IP, Figure 1.1), which can be used as a measure of the magnitude of the external load on the tibia during running.[74] Loading rate, also derived from the vertical GRF, is often used as a measure for bone strains in the tibia, since it provides an approximation of the rate of external load on the tibia during running.[75] The GRF will be attenuated through joint structures and soft tissue in the body, but at the level of the tibia a large proportion of the GRF will be transmitted to the bone.[76] Loading parameters for the tibial bone can be calculated using GRF, as described below.

A typical GRF curve during running is displayed in Figure 1.1. The amplitude of the GRF signal depends on body weight, running speed and running kinematics and kinetics. Differences in running kinematics and kinetics can lead to differences in loading and thus in the shape of the GRF signal. A vertical GRF signal typically displays two peaks: the initial, or impact peak (IP) and a second, larger, active peak. The IP results from the collision of the foot with the ground, and induces a high-frequency component at the beginning of the foot contact phase, reaching the peak within 50 ms from initial contact.[77] The second peak results from an active push-off from the ground.[78] Overall, bone strains are highest at the moment the foot collides with the ground, representative for IP.[71] According to the study of Giddings et al[79], the shape of the vertical GRF curve is very similar to the shape of the ankle joint contact force curve, indicating that vertical GRF is strongly related to bone loading. Besides peak impact force (IP), instantaneous vertical loading rate (IVLR) and mean loading rate (LR), defined as the respectively the maximum and the mean slope of the vertical GRF curve between 20 and 80 percent of the interval between foot strike and IP,[71] are often used as a measure of impact loading. High LR, caused by a more rapid force application, has been associated with larger strains on the tissues of the lower limb.[75]

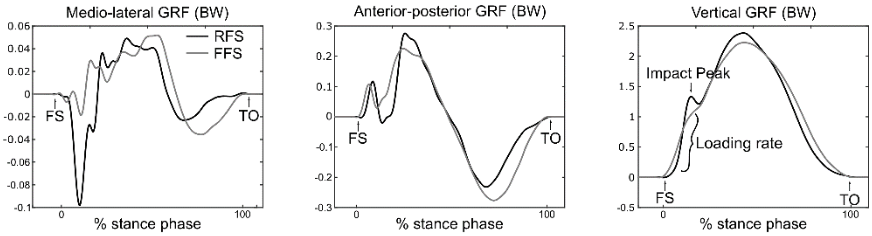

Figure 1.1: Three components of a typical GRF pattern with (black line) and without (grey line) detectable impact peak. BW = body weight, RFS = rearfoot strike, FFS = forefoot strike, FS = foot strike, TO = toe-off. Loading rate is determined as the slope of the vertical GRF between 20 and 80 % of the interval between FS and TO.

Influence of running kinematics on loading

The cumulative load on a specific structure is defined by three factors: the magnitude of the load per stride, the distribution of the load over the structure and the number of strides per running session.[56] The first two factors are influenced by running kinematics and kinetics. Many studies have aimed to determine which kinematic and kinetic variables are associated with higher loading in order to identify risk factors for overuse injury development. Although there are intuitive relationships between running style and running performance and between running style and injury risk, establishing these relationships is not straightforward, judged by the inconclusive findings of the studies on this topic.[4,8]

Landing with a more anterior positioned foot with respect to the knee was associated with higher IP and LR.[80] Step rate was found to influence loading of the hip and knee joints, with increased step rate by just 5% being successful in decreasing joint loading during running.[81] Increased leg stiffness, defined as the maximal vertical GRF divided by the change in vertical leg length, was associated with increased peak forces and LR.[82] A forefoot strike pattern, in which the ball of the foot hits the ground first, generally leads to lower LR and IP compared to a heel strike pattern, in which the heel of the foot hits the ground first. In a forefoot strike pattern, several mechanisms help to decrease the vertical acceleration of the centre of mass during the landing phase. The shock of the landing is partially absorbed by the eccentric work of the ankle plantar flexor muscles and the larger ankle dorsiflexion and eversion (outward rotation of the foot along the longitudinal axis) excursion. This causes reduced IP and LR, as displayed by the grey line in Figure 1.1).[83] However, a forefoot strike pattern increases Achilles tendon loading during initial contact with the ground.[84] Since the ankle is more plantar flexed when landing in a forefoot strike pattern, the GRF vector is located anterior with respect to the ankle. In order to control the ankle angle during stance phase, a higher internal ankle plantar flexor moment is necessary. Therefore, the plantar flexor muscles have to produce higher forces, which are transmitted through the Achilles tendon, leading to higher Achilles tendon loading.[85] Adopting a running pattern that reduces loading per step, such as an increased step frequency with decreased leg stiffness and a midfoot strike pattern, is often proposed as a way to reduce injury risk. However, evidence from prospective studies on the effectiveness of adopting such a running pattern for injury prevention is currently missing. Furthermore, such a running pattern may not contribute to improving running economy and speed, and may decrease the stimulus necessary for tissue adaptation.

Loading capacity of bone and tendon

Structure specific loading capacity refers to the structure's ability to withstand load without sustaining injury.[56] The loading capacity depends on the mechanical properties of the specific structure.[56] For bone, these mechanical properties are determined by bone mass, BMD and the distribution of bone mass around the bending axis. These properties influence the resistance of the bone against bending forces.[70] For tendon, these mechanical properties include tendon stiffness, cross-sectional area and Young's modulus. These characteristics influence the resistance of the tendon against pulling forces.

Loading capacity is influenced by many factors, including previous training, previous injury, genetic factors, age, diet, sleep and time between training sessions.[56] Loading tissues within the loading capacity and allowing adequate time in between loading sessions, creates an adaptive environment. This environment leads to positive remodelling of the tissues, thereby increasing the loading capacity of the tissue.[8] However, although mechanical loading is necessary to provide a stimulus for tissue adaptation, there is a fine line between loading the tissues and exceeding the loading capacity. Tissue loading above the physiological range will result in traumatic injury, which is not very common during running. However, repeated loading, even within the physiological range, can cause microdamage. Normally, this microdamage initiates remodelling processes that eventually strengthen the tissues.[86] However, without sufficient rest in between loading cycles, the loading capacity reduces, causing accumulation of tissue damage.[87,88] Therefore, in order to achieve positive adaptation of bone and tendon structures, structures need to be loaded within their loading capacity and with enough rest in between loading sessions. For novice runners this means that adaptations will depend on the individual loading patterns during running, the amount of rest between sessions (which is fixed for a fixed training program) and the structure specific loading capacity (e.g. mechanical properties). Currently, the extent of the musculoskeletal adaptation during a 12-week running program is unknown, as are the relationships between individual loading patterns during running and musculoskeletal adaptation.

GENERAL OBJECTIVE

Running programs for absolute beginners are very popular. The effects of following such a running program on cardiorespiratory fitness have been well established.[2,3] However, not much is known about the effects of a typical short-term running program on the musculoskeletal system. For this work, we studied a group of novice runners following a typical, 12-week running program to study short-term training effects of running on the musculoskeletal system. More specific, the aim of this thesis was to report the effects of a 12-week running program on running kinematics and kinetics, geometry and density of the tibial bone and Achilles tendon stiffness.

General objective: to determine the influence of a typical 12-week running program on running kinematics and kinetics, tibial bone geometry and density and Achilles tendon stiffness in novice runners.

A running program for beginners changes the mechanical environment of the musculoskeletal system, imposing mechanical loads on the tissues. When loaded within the loading capacity of the tissues and when given sufficient recovery time in between training sessions, tissues will respond to this increased mechanical load by getting stronger. Therefore, we expect that healthy subjects who follow a running program for beginners will develop higher BMD and higher Achilles tendon stiffness. In addition, we expect them to change their running kinematics and kinetics in such a way that they will become more efficient and less prone to injuries. We thereby hypothesize that a 12-week running program will cause adaptations similar in direction to the long-term adaptations we see in well-trained runners.

General hypothesis: 12 weeks of running training in novice runners changes running kinematics and kinetics as well as the loading capacity of the tibial bone and Achilles tendon.

SPECIFIC OBJECTIVES

Chapter 2: Changes in running kinematics and kinetics after a 12-week running program for beginners

It is well established that trained runners have better running economy than untrained runners[89]. Also, a recent review found that novice runners have higher injury incidence compared to trained runners[5]. Running economy and injury risk are both affected by running kinematics and kinetics. One may therefore expect that trained runners, due to long-term adaptations to running training, have more economical and less injury prone running kinematics and kinetics compared to novice runners. However, the short-term training effects on running kinematics and kinetics are unknown.

Objective: to study the influence of a 12-week running program on running kinematics and kinetics in novice runners.

To gain insight in the training effect of a 12-week running program, we measured running kinematics and kinetics before and after a 12-week running program. Since training effects on running kinematics and kinetics are not well documented, it is difficult to hypothesize what to expect in terms of changes in running kinematics and kinetics with training. Both running economy and injury risk are associated with specific running kinematics and kinetics characteristics. Better running economy can be achieved by running with lower vertical oscillation of the centre of mass, greater leg stiffness, less leg extension at toe-off, and lower braking forces[90]. Injury risk may be lowered by decreasing hip adduction, knee internal rotation and ankle pronation during stance, and by lowering LR.[75,91,92] Given the better running economy and lower injury rates in trained runners, we expect that with training, running kinematics and kinetics adapt towards a movement pattern that is more economical and less injury-prone.

Hypothesis: after 12 weeks of training, novice runners will adopt running kinematics and kinetics that are associated with lower injury risk and better running economy.

Chapter 3: Distal tibia geometry increases in female novice runners after a 12-week running program

Increased physical activity involving impact forces has been proposed as a way to increase bone strength.[93] This view is supported by cross-sectional studies that found higher BMD and/or larger cortical bone size in people who engage in sports that involve high impact forces, such as running and jumping.[20–23,94] However, it is unknown whether 12 weeks of running training are sufficient to cause adaptations in the tibia. Therefore, we measured tibial bone parameters before and after a 12-week running program to determine short-term training effects of running on the density and geometry of the tibia.

> Objective 1: to determine the effect of a 12-week running program on tibial bone geometry and density in novice runners.
>
> Objective 2: to relate loading parameters (peak vertical GRF, IP and LR) to changes in bone properties.

In sedentary people, starting a running program changes the mechanical environment of the bones of the lower limb. Running provides repeated impact forces on the bones, which can be beneficial for increasing bone geometry and density.[14] Therefore, we expected that bone geometry, especially in the distal tibia, would increase after 12 weeks of running training.

> Hypothesis 1: Bone density and geometry (total area and cortical area) of the tibia will increase after a 12-week running program for novice runners.
>
> Hypothesis 2: Tibial loading parameters during running are positively related to increase in bone density and geometry after a 12-week running program for novice runners.

Chapter 4: Achilles tendon adaptation and Achilles tendinopathy in running: a narrative review

The Achilles tendon is a structure that is heavily loaded during running. Normally, tendon tissue adapts to increased mechanical loading by changes in structure and size, making it more resistant to strain.[38] However, the Achilles tendon is also sensitive to overloading and therefore frequently injured in novice runners.[51,52] Chapter 4 contains a narrative review of the available literature on Achilles tendon loading during running and Achilles tendon adaptation in runners.

Objective: to review the literature on Achilles tendon loading and adaptation during running.

Chapter 5: No adaptation in Achilles tendon stiffness after a 12-week running program for beginners

Tendons adapt to repeated loading, especially high strain loading, by changes in size, structure and stiffness. Runners have thicker Achilles tendons compared to non-runners.[46,95] Athletes in sports involving high Achilles tendon loading such as sprinting and ski jumping, have higher Achilles tendon stiffness than controls.[48,96,97] On the other hand, people with Achilles tendinopathy, an overuse injury characterized by swelling and pain in the Achilles tendon area, have lower tendon stiffness.[98] Increase in tendon stiffness therefore seems to be a positive adaptation. However, it is unknown whether 12 weeks of running provide enough tendon loading to cause adaptations in Achilles tendon stiffness.

Objective 1: to determine the effect of a 12-week running program on Achilles tendon stiffness in novice runners. Objective 2: to determine the relationship between Achilles tendon loading during running and change in Achilles tendon stiffness.

Sprint athletes and ski jumpers did show higher Achilles tendon stiffness compared to inactive people,[96] indicating that the Achilles tendon adapts to high-magnitude loading. However, the effect of a 12-week running program on Achilles tendon stiffness is unclear. The magnitude of Achilles tendon loading during running varies greatly with body weight, running speed and running kinematics and kinetics, in particular with foot strike pattern.[85] Therefore, a second aim of this study was to explore the relationship between Achilles tendon loading during running and change in Achilles tendon stiffness.

Hypothesis 1: Achilles tendon stiffness will increase after 12 weeks of running in novice runners.

Hypothesis 2: Achilles tendon loading during running is positively related to changes in Achilles tendon stiffness after a 12-week running program for beginners.

Chapter 6: Novice runners show greater changes in kinematics with fatigue compared with competitive runners.

In chapter 2, we first examined the effect of 12 weeks running training on running kinematics and kinetics. However, 12 weeks may be too short to induce changes in running kinematics and kinetics. For the final chapter, we wanted to explore the effects of training status in a cross-sectional study, comparing novice runners to well trained, competitive long-distance runners. One study has reported differences in running kinematics and kinetics between competitive and recreational runners, including pelvic tilt, knee flexion and ankle eversion[99], but the differences between competitive runners and novice runners are unknown.

During a training session, runners will get fatigued. Previous studies have shown larger impact accelerations and LR during running with in a fatigued state, indicating that the tissue load per stride increases with fatigue.[100,101] Studies on running in a fatigued state found that peak ankle pronation[102], knee internal rotation[103,104] and rearfoot eversion[100,102] increased compared to a fresh state. All these variables have been identified as risk factors for overuse injuries.[91,105,106] Therefore, fatigue seems to magnify risk factors for developing overuse injuries. Training status might influence the effect of fatigue on running kinematics and kinetics. We therefore measured running kinematics before and after a run until voluntary exhaustion in a group of novice runners and in a group of well trained long distance runners.

Objective: to determine the influence of training status on running kinematics during an exhaustive run.

As muscles get fatigued over the course of a run, runners may adapt their kinematics. Competitive long distance runners, who are trained to maintain good running form throughout an exhaustive training session, may show smaller changes in running kinematics during a fatiguing run than novice runners. Furthermore, experienced runners may be stronger in specific muscle groups, such as the hip abductors, enabling them to maintain their running kinematics with fatigue. Larger changes in running kinematics and kinetics with fatigue in novice runners may also explain the higher injury rates in novice runners. Therefore, we hypothesize that running kinematics are affected by both training status and fatigue.

Hypothesis: novice runners show greater changes in kinematics during an exhaustive run compared to well trained, competitive long distance runners.

METHODS

An overview of the methods for data collection and the main outcome variables for each study is given in Table 1.1.

	Subjects	**Intervention**	**Protocol**	**Measurements**	**Main outcome variables**
Chapter 2 (kinematics/ kinetics)	27 novice runners	12-week running program	Overground running	Marker trajectories, GRF, EMG	Joint angles, joint moments, LR, IP, peak GRF
Chapter 3 (tibia)	11 female novice runners	12-week running program	Overground running	Marker trajectories, GRF, EMG, bone geometry, bone density	Bone mass, area, density; cortical area, cortical density, trabecular density, LR, IP
Chapter 5 (Achilles tendon)	Experimental group: 22 novice runners	12-week running program	Overground running	Marker trajectories, GRF, EMG, Achilles tendon cross-sectional area, Achilles tendon stiffness	Achilles tendon stiffness, ankle plantar flexor moment
	Control group: 16 inactive subjects			Achilles tendon cross-sectional area, Achilles tendon stiffness	Achilles tendon stiffness

Chapter 6 (fatigue)	15 novice runners 15 competitive, long-distance runners	Run to voluntary exhaustion	Fatigue protocol (treadmill)	Marker trajectories, GRF, EMG	Joint angles

Table 1.1: overview of the measurements performed for each study and the main outcome variables that were extracted from these measurements and used in the different chapters.

Subjects

All participants were recruited through social media, flyers at the university sports centre, and advertisement in a local newspaper. Participants were screened prior to participation using a questionnaire, and were excluded if they had any pulmonary, neurological or cardiovascular disease, were obese (BMI > 30), older than 60 years, or had any musculoskeletal injuries in the 6 months prior to participation. Participants (except for the competitive runners in chapter 6) were also excluded if they participated in any regular, weight-bearing sport for more than one hour per week in the year prior to participation. Additional inclusion criteria applied to chapter 6 to ensure that only very well trained athletes were included in the competitive group. Competitive runners were included if they participated regularly in competitions and ran more than 70 km/week for the male athletes or more than 50 km/week for the female athletes. For chapter 3, female participants were excluded if they were menopausal or amenorrheic.

Participants gave written informed consent in accordance with the declaration of Helsinki. The local ethics committee (Commissie Medische Ethiek KU Leuven) approved the studies under number S55278 (chapters 2, 3 and 5) and S55656 (chapter 6)

A flowchart of the subjects included in each study is shown in Figure 1.2. Control subjects were only included in the Achilles tendon study and were therefore not included in the running analysis, as they were not asked to run during the study. Since recruitment for the running analysis started before the final protocol for Achilles tendon testing was ready, not all participants participated in the tendon measurements. In addition, compliance for the pQCT measurements was low. For each subject in chapter 3 and 5, good pre- and posttest overground running data were necessary to associate loading variables with tissue adaptation variables. Since there were technical problems with the overground running data, the number of participants included in these studies is lower than the number of participants that underwent tendon and bone testing.

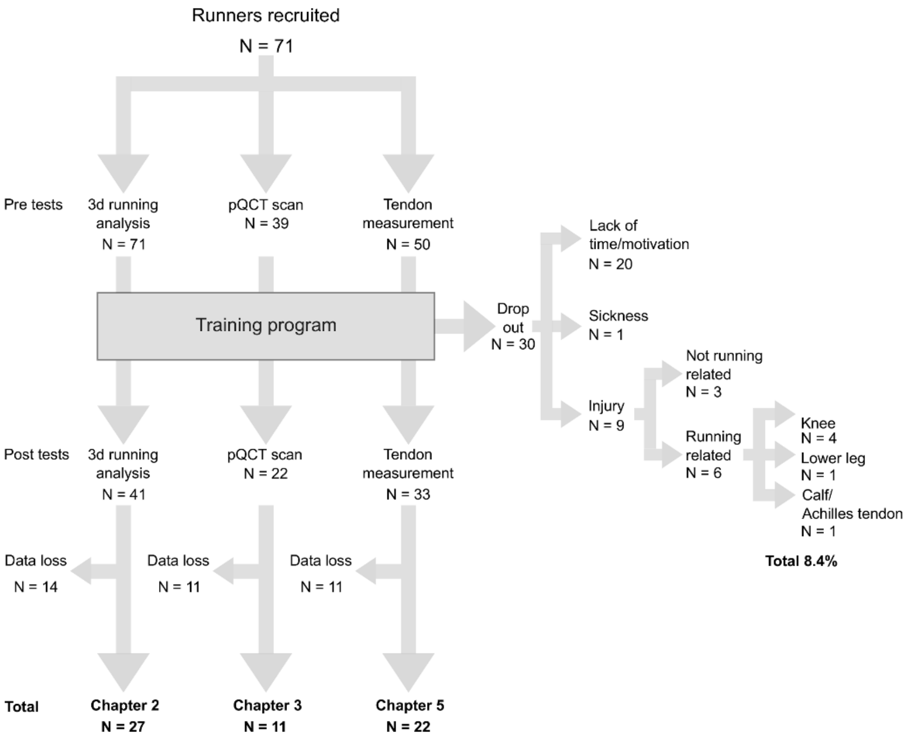

Figure 1.2: subject flowchart

Sample size

Sample size of the group of novice runners was based on studies measuring changes in bone area of the distal tibia and Achilles tendon stiffness with training. Smock et al.[107] found a difference in total bone area at 4% of the distal tibia between female runners (967.0 ± 98.4) and inactive controls (868.9 ± 97.9). A power analysis with an alpha level of 0.05 and a beta of 0.2 yielded a required sample size of 16. Albracht et al.[39] studied Achilles tendon stiffness before and after a resistance training program. The training intervention in Albracht's study was of a similar duration (14 weeks) to our study, but consisted of a different exercise mode: resistance training. Since no running studies of similar duration to our study were available, Albracht's study was used for the power calculation. In the study of Albracht et al., Achilles tendon stiffness changed from 272 (SD: 48) to 315 (SD: 53) N/mm. Given an alpha level of 0.05 and a beta of 0.2, the required sample size was 11 subjects. Since we expected a high drop out rate of up to 50% of participants, we recruited 71 participants for the training program.

For Chapter 6, sample size was calculated based on the results of Derrick et al.[108], who used a similar fatigue protocol. Based on their findings (peak knee angle 127.7 ± 1.4 degrees pre-fatigue and 123.8 ± 1.5 post-fatigue; peak rearfoot angle -6.5 ± 1.4 pre-fatigue and -7.8 ± 1.4 post-fatigue) a sample size of 12 subjects per group with an effect size of 0.93 and a power of 0.9 was calculated. To account for possible data loss, fifteen novice runners and fifteen competitive long-distance runners volunteered to participate in the study.

Experimental procedure

For Chapters 2, 3 and 5, in which adaptations after a 12-week running program were studied, subjects followed the 12-week running program as described in Appendix II. Before starting the program and after finishing the program, subjects underwent testing in the movement lab (3d running analysis and Achilles tendon stiffness measurement). Subjects were tested within two weeks before starting the running program and within two weeks after finishing the program. Peripheral quantitative tomography (pQCT) scans of the lower legs were taken in the Centre for Densitometry, UZ Leuven.

For Chapter 6, in which the influence of training status and fatigue on running kinematics was studied, a cross-sectional study design was used. Subjects came into the Movement and Posture Analysis Laboratory Leuven twice, with one week in between sessions. In order to determine a pace for the fatiguing run, which the participants had to be able to sustain for at least 10 minutes but no longer than 30 minutes, participants performed a 3200 m time trial at maximum effort on an outdoor running track. The average running speed during this time trial was used in the second measurement. During the second session, participants performed a fatigue protocol. After warming up (two minutes walking and two minutes slow jogging), they ran at the average pace of their time trial until they were exhausted and indicated that they wanted to stop running. Running kinematics were measured during the first and last minute of the test.

Intervention

Participants in the studies from Chapter 2, 3 and 5 followed a running program for beginners. The program consisted of three training sessions per week, for 12 weeks. Supervised training sessions were organized twice per week at the University sports centre. Participants were encouraged to do the third training session individually. Subjects were allowed to choose between two training programs: one for absolute beginners that led from 1 to 30 minutes of continuous running and one for slightly fitter subjects that led from 10 to 45 minutes of running. This option was introduced since several participants indicated that they were not motivated to do the first program because it would be too easy. Both programs consisted of alternating running and walking intervals. The running distance per session was increased every week.

Supervised training sessions started with a short warming-up including light dynamic stretching. Participants were instructed to run at their own, comfortable pace and wore their own running shoes. Participants recorded their weekly training distance in a log book, in which they were also instructed to note any pain or injury. The log book is included in Appendix III. In case of an injury, the participant was referred to a sports physician. Training programs are added in appendix II.

Measurements and data processing

Three-dimensional running analysis

In all subjects, except for the control subjects from Chapter 5, a 3-dimensional running analysis was performed to measure running kinematics and/or kinetics. A 10-camera Vicon system, capturing at 150 Hz was used to record trajectories of 48 reflective markers, placed on anatomical landmarks on the subjects' skin (Figure 1.3). An overview of the markers used in the 3-dimensional running analysis is given in Appendix IV. Subjects wore standardized, neutral running shoes for the measurement (Asics Landreth 7), in which five holes per shoe were made. Foot markers placed on wands were attached to the skin of the feet and protruded through the holes in the shoes. Using this method, as opposed to sticking the markers on the outside of the shoe, we aimed to capture the motion of the feet more accurately. Measuring the movement of the foot inside the shoe is important because movement of the shoe heel counter is independent of the rearfoot of the shod foot and can vary by 5–10 degrees.[109] This method has previously been applied to study foot movement during shod walking and running .[110] The holes in the shoes were 20 mm in diameter. In a previous study[109,111], shoe holes as small as 16mm did not cause marker wands to touch the shoe during walking and running. This was checked using a high speed video camera during the measurement (unpublished data). Although Bishop et al.[112] recommend holes of 25mm in order to prevent disruption of marker trajectories caused by the marker wand touching the upper of the shoe, holes as large as 25mm can compromise the integrity of the shoe, according to a study by Shultz and Jenkyn.[113] Therefore, holes of 20 mm in diameter were chosen. Strong, self-centring magnets were used to attach the marker wands to the feet, which allowed for accurate replacement of the markers in case they fell off between trials. In all measurements, subjects were measured while running overground and on an instrumented treadmill. GRF during overground running were recorded using a force platform (AMTI, type OR6-7) embedded in the floor of the movement lab. In addition, an instrumented treadmill (Forcelink, Culemborg, the Netherlands) was used to measure GRF.

Although all subjects were measured both on the treadmill and while running overground, we made choices regarding which data to report. Both treadmill and overground running have advantages and disadvantages. The treadmill allows for measuring running at a constant speed and measuring multiple, consecutive steps. On the other hand, the treadmill changes the kinematics of running significantly compared to overground running.[114] In Chapters 2, 3 and 5, only overground running data were used because it was not possible to connect the GRF measured with our instrumented treadmill with the kinematics in the software that we used (Bodybuilder 3.6.4), making it impossible to use the GRF from the treadmill. Furthermore, we had to consider that the novice runners trained overground during the 12-week running program. Therefore, it made sense to test overground running as well. In Chapter 6, treadmill data were used since this allowed for continuous running during the fatigue protocol. Unfortunately, we were not able to report kinetics in this chapter because we could not use the GRF data from the treadmill. All studies required good pre- and posttest trials to compare parameters before and after the intervention. In studies 3, 5 and 6, trials from both legs were used in order to use the maximum available amount of data points and to increase statistical power. We chose to enter the data from the left and the right leg independently into the analysis. Although the left and the right leg are inherently belonging to the same subject, both loading during running and adaptation to a running program can differ substantially between both legs, which is one of the reasons that injuries often occur unilaterally. On the other hand, in study 2, it was not possible to create a data set with good quality running data of both legs, pre- and posttest, for every subject. Therefore, in order to optimize the amount of data points, data of one leg per subject were used.

Figure 1.3: 48 reflective markers were placed on anatomical landmarks on the body. Markers on the feet protruded through holes in the shoes. Marker locations are described in appendix IV.

Marker trajectories were filtered using a 4^{th} order low pass Butterworth filter with a cut-off frequency of 15 Hz. Joint angles were calculated from the marker trajectories in Vicon Body Builder version 3.6.4. The marker model was an adapted Plugin-Gait model, including 16 body segments: trunk, pelvis, left and right upper arm, forearm + hand, thigh, shank, rearfoot, midfoot + forefoot, and toe (Table 1.2, Figure 1.4). Trunk and pelvis angles were calculated relative to the lab coordinate system, while the other segment angles and moments were calculated with respect to the proximal segment. Net joint moments, the sum of the moments caused by the forces developed by the muscles and other structures crossing that joint,[115] in the hips, knees and ankles were calculated using an inverse dynamics approach. This approach assumes that the foot, shank and thigh are rigid segments, connected by joints. Measured GRF and kinematics computed from the marker trajectories are inserted into the Newton-Euler equations of motion ($F = ma$; $M = I\alpha$).[115]

Segment	Origin	Longitudinal axis	Mediolateral axis
Trunk	T10	C7-T10	Left shoulder – right shoulder
Pelvis	Midpoint of left and right ASIS and left and right PSIS	Midpoint ASIS – midpoint PSIS	Left ASIS – Right ASIS
Thigh	Hip joint centre: x (-0.31*Pelvis_depth), y (0.38*Pelvis_width), z (0.096 * Leg length)	Hip joint centre – knee joint centre	Lateral epicondyle – medial epicondyle
Shank	Knee joint centre: Lateral epicondyle – medial epicondyle	Knee joint centre – talocrural joint centre	Lateral epicondyle – medial epicondyle
Midfoot + forefoot	Subtalar joint: x (navicular bone), y (talocrural joint centre), z (navicular bone)	Toe – Subtalar joint	Navicular bone – Subtalar joint
Rearfoot	Talocrural joint centre: lateral malleolus – medial malleolus	Talocrural joint centre – heel	Lateral heel – medial heel
Toe	MTP joint: MTP5-MTP1	MTP joint – toe	MTP5-MPT1

Table 1.2: kinematic model definitions.

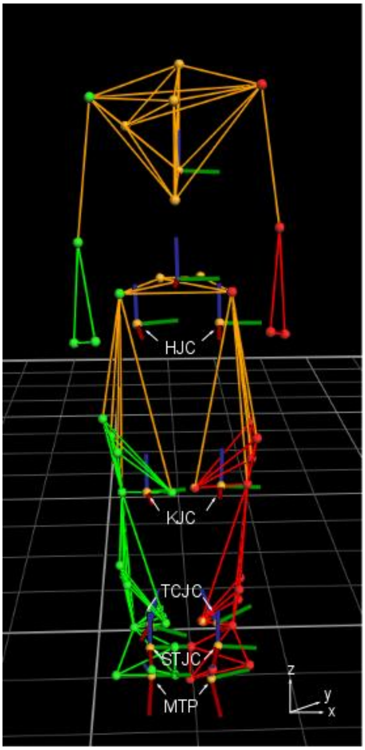

Figure 1.4: segment and joint centre definitions. HJC = hip joint centre, KJC = knee joint centre, TCJC = talocrural joint centre, STJC = subtalar joint centre, MTP = metatarsophalangeal joint.

pQCT scans

Bone geometry and density of the lower legs (Chapter 3), were measured using pQCT scans (XCT-2000, Stratec, Germany). BMD can be measured non-invasively using dual-energy x-ray absorptiometry (DEXA), dual-photon absorptiometry, or pQCT. DEXA scans used to be the golden standard for a long time, but have the drawback that they cannot differentiate between cortical and trabecular bone. pQCT uses X-rays and calculates bone density based on the linear X-ray absorption coefficients of the tissues through which it passes. It can differentiate between cortical and trabecular bone, and is therefore a good method for monitoring changes in geometry and density of both cortical and trabecular bone.[116] Szabo et al. tested the reproducibility of the XCT-2000 scanner at the tibia in women, finding high reproducibility values (1.5% for density and 2.8% for area at the distal tibia), indicating that this method is suitable for detecting small changes in bone properties.[117]

Scans were taken at 4, 14 and 38% of the tibia length, measured from the distal end of the tibia (Figure 1.5). Tibial length was measured manually between the medial malleolus at the ankle and the medial knee joint cleft. The 4% site (distal tibia) is often used to calculate trabecular bone parameters and the 38% site is often used to calculate cortical bone parameters.[118] Outcome parameters calculated from these scans included mass, area, density, trabecular density, cortical area and cortical density.

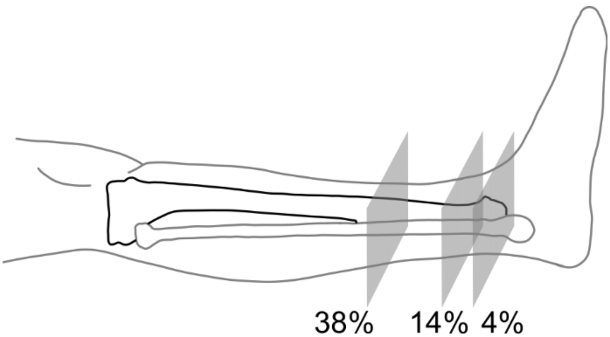

Figure 1.5: pQCT scans were taken at 4%, 14% and 38% of the tibial length, measured from the distal end of the tibia.

Achilles tendon stiffness

In Chapter 5, Achilles tendon stiffness was measured. Achilles tendon stiffness is defined as the elongation of the tendon when pulled on by a given force.[119] We used a non-invasive method for measuring tendon mechanical properties in vivo.[64,120,121] In this method, tendon length change is measured using ultrasonography, while the force pulling on the tendon is defined as the ankle plantar flexor moment during maximal voluntary contractions, divided by the Achilles tendon moment arm. Ankle moment was measured using a combination of a force transducer and motion capture. In order to compute Achilles tendon stiffness, the following parameters must be calculated: Achilles tendon elongation, ankle plantar flexor moment and Achilles tendon moment arm (MA_{int}). The measurement setup was adapted from the study of Kongsgaard et al.[122]. Using force transducer and ultrasound measurements during isometric plantar flexion contractions, they measured Achilles tendon stiffness on two separate days. They found a between-day correlation coefficient of 0.84 for Achilles tendon stiffness, indicating good reproducibility of this method.

Subjects were positioned prone on an examination table, with their feet over the back edge of the table. A rigid foot plate was strapped to the subject's foot. A cable, connected to a force transducer (HBM U2A, Darmstadt, Germany), was attached to the foot plate at the level of the metatarsal heads (Figure 1.6). Reflective markers were attached to the lower leg, foot and cable, in order to measure ankle angle and the external moment arm. A linear ultrasound probe (Telemed Echoblaster 128, Vilnius, Lithuania), capturing at 30 Hz, was attached to the calf of the subject at the level of the musculotendinal junction (MTJ) using a custom-made cast.

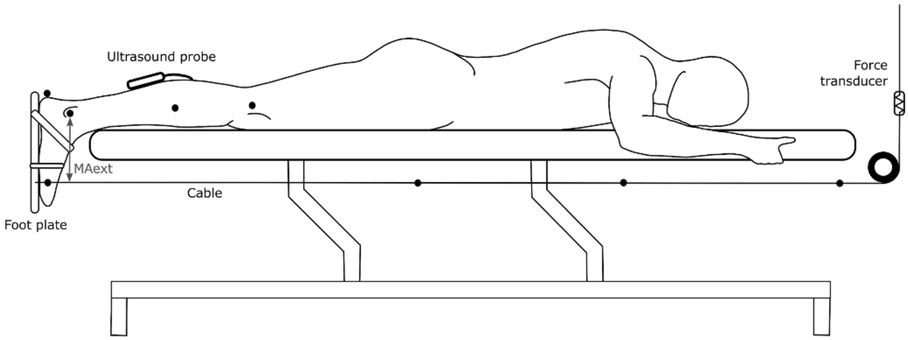

Figure 1.6: Setup for the measurement of Achilles tendon stiffness. MAext = external moment arm, calculated from the marker positions and used to calculate Achilles tendon force.

First, the internal Achilles tendon moment arm was calculated using the tendon travel method.[123–125] The internal moment arm of the Achilles tendon describes the distance from the centre of rotation of the ankle joint to the line of pull of the triceps surae muscle. A reliable estimate of this moment arm is necessary to accurately calculate the Achilles tendon force during an isometric contraction, which is used to calculate Achilles tendon stiffness. The tendon travel method calculates this moment arm as the ratio of the linear displacement of the tendon to the angular excursion of the ankle joint during a passive rotation of the ankle using the principal of virtual work. We calculated the internal moment arm by dividing the change in position of the MTJ ($\Delta\mathrm{MTJ}$) over a passive 15 degree ankle rotation by the change in ankle angle in radians:

$$\mathrm{MA_{int}} = \frac{\Delta\mathrm{MTJ}}{\Delta\text{ankle angle}}$$

The advantage of this method is that the moment arm can be computed without using additional and costly equipment such as MRI or CT scanners. Achilles tendon moment arms calculated using the tendon travel method correlated strongly with moment arms obtained from MR images.[125]

The method described above was also used to determine how much the MTJ moves per degree of ankle rotation. This calculation is necessary, because some ankle rotation occurs during the performed 'isometric' contractions. High ankle moments cause deformation of the padding of the examination table, the soft tissue of the foot, and the cable, pulley and foot plate construction.[126] To determine the Achilles tendon moment arm and the ankle angle correction (passive trial), the subject was instructed to relax his/her leg, while the ankle was rotated over approximately 40 degrees by the researcher. To determine Achilles tendon stiffness, participants performed maximal voluntary ramp contractions (ramp MVC's), for which they were instructed to build up the force over three seconds to maximal force, and then relax over three seconds to full relaxation. During all measurements, marker trajectories, force transducer signal and ultrasound images were recorded simultaneously and synchronized using a manual trigger. Two passive trials and three ramp MVC's were recorded per leg.

Ankle angle during the passive and active trials was calculated from the marker trajectories in Vicon Body Builder. MTJ position was tracked manually using custom-made Matlab code. For each frame, coordinates of the MTJ on the ultrasound image were stored, and the coordinates of the MTJ in the first frame were subtracted to calculate ΔMTJ (Figure 1.7).

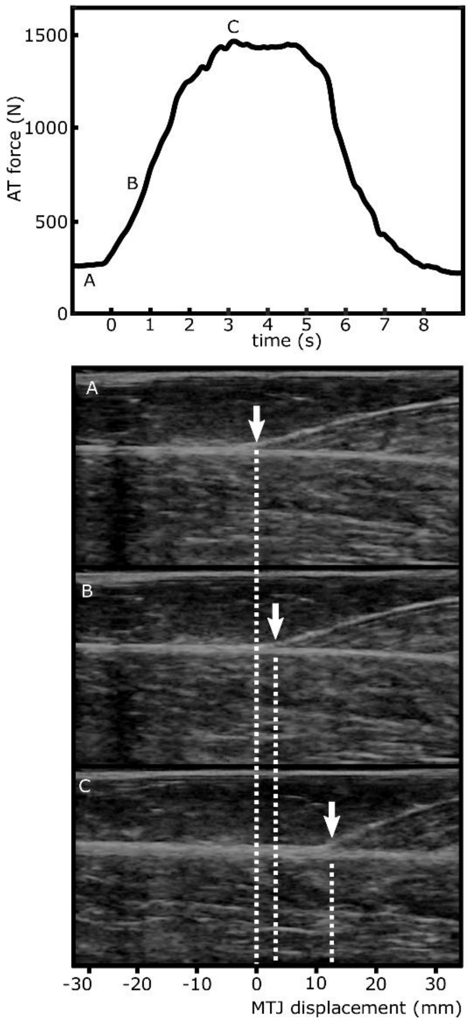

Figure 1.7: MTJ displacement during an isometric ankle plantar flexion. Subjects were instructed to gradually build up and release the plantar flexor force (upper panel). A: relaxed state, B: contraction (slight MTJ displacement), C: maximal contraction (maximal MTJ displacement).

The force signal was filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 10 Hz. ΔMTJ was filtered using a 4th order low-pass Butterworth filter with a cut-off frequency of 6 Hz. Internal ankle plantar flexor moment was calculated by multiplying the force with the external moment arm, calculated as the shortest distance from the ankle rotation centre (middle between medial and lateral malleoli) to the cable (Figure 1.6). Achilles tendon force (F_{AT}) was calculated by dividing ankle plantar flexor moment by MA_{int}.

$$F_{AT} = \frac{F_{cable} * MA_{ext}}{MA_{int}}$$

Change in Achilles tendon length (ΔL) during the ramp MVC was calculated as ΔMTJ. Achilles tendon stiffness was calculated from the strongest ramp MVC as the slope of the F_{AT} – ΔL relationship from 50-100% of maximal F_{AT}.

$$\text{Achilles tendon stiffness} = \frac{\Delta L}{\Delta\, F_{AT}}$$

Statistics

Since all studies involved measurements taken before and after an intervention (12-week running program or exhaustive run), a repeated measures ANOVA was used in all studies to determine the effect of the intervention on the dependent variables. Dependent variables were first checked for normality. If data were not normally distributed, a Wilcoxon signed rank test was used. Correlations between loading variables and (change in) dependent variables were calculated using Pearson's correlation coefficient. SPSS version 22 was used for statistical analyses.

In Chapter 2 (the influence of training on running kinematics and kinetics), peak joint angles and moments were taken as dependent variables because we focused on variables that were associated with running economy and injury risk in the literature. However, the study of Chapter 6 (the influence of fatigue on running kinematics and kinetics), had a more explorative character. Therefore, we did an additional analysis of the waveforms of the joint angles during a whole stride using Statistical Parametric Mapping (SPM). This method uses random field theory to determine the significance of differences between two mean curves.[127] The advantage of this method is that not only differences in peak joint angles can be detected, but also differences in amplitude and timing of the joint angles.

REFERENCES

1 Scheerder J, Breedveld K, editors. *Running across Europe*. Basingstoke (UK), Palgrave Macmillan, 2015.

2 Scharhag-Rosenberger F, Meyer T, Walitzek S, et al. Time course of changes in endurance capacity: A 1-yr training study. *Med Sci Sports Exerc* 2009; 41(5):1130–1137.

3 Hespanhol Junior LC, Pillay JD, van Mechelen W, et al. Meta-Analyses of the Effects of Habitual Running on Indices of Health in Physically Inactive Adults. *Sport Med* 2015; 45:1455–1468.

4 Ferber R, Hreljac A, Kendall KD. Suspected mechanisms in the cause of overuse running injuries: a clinical review. *Sports Health* 2009; 1(3):242–246.

5 Videbaek S, Bueno AM, Nielsen RO, et al. Incidence of Running-Related Injuries Per 1000 h of running in Different Types of Runners: A Systematic Review and Meta-Analysis. *Sport Med* 2015; 45:1017–1026.

6 Baltich J, Emery CA, Whittaker JL, et al. Running injuries in novice runners enrolled in different training interventions: a pilot randomized controlled trial. *Scand J Med Sci Sports* 2017; 27:1372–1383.

7 Lopes AD, Hespanhol Júnior LC, Yeung SS, et al. What are the main running-related musculoskeletal injuries? A Systematic Review. *Sport Med* 2012; 42(10):891–905.

8 Hreljac A. Impact and Overuse Injuries in Runners. *Med Sci Sport Exerc* 2004; 36(5):845–849.

9 Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing the response to loading. *Nat Rev Rheumatol* 2010; 6:262–268.

10 Hamstra-Wright KL, Huxel Bliven KC, Bay C. Risk factors for medial tibial stress syndrome in physically active individuals such as runners and military personnel: a systematic review and meta-analysis. *Br J Sports Med* 2015; 49:362–369.

11 Kastelic J, Galeski A, Baer E. The multicomposite structure of tendon. *Connect Tissue Res* 1978; 6(1):11–23.

12 Burr DB, Martin RB, Schaffler MB, et al. Bone remodeling in responso to in vivo fatigue microdamage. *J Biomech* 1985; 18(3):189–200.

13 Burr DB, Milgrom C, Boyd RD, et al. Experimental stress fractures of the tibia. Biological and mechanical aetiology in rabbits. *J Bone Jt Surg* 1990; 72(3):370–375.

14 Zernicke RF, Judex S, Lorincz C. Adaptation of biological materials to exercise, disuse and aging. In: Nigg Benno M., Herzog W, editors. *Biomech. musculo-skeletal Syst.* 3rd ed. Chichester, UK, John Wiley and Sons, 2006. p. 226–240.

15 Komi P V., Fukashiro S, Jarvinen M. Biomechanical loading of Achilles tendon during normal locomotion. *Clin Sports Med* 1992; 11(3):521–531.

16 Nikander R, Kannus P, Rantalainen T, et al. Cross-sectional geometry of weight-bearing tibia in female athletes subjected to different exercise loadings. *Osteoporos Int* 2010; 21(10):1687–1694.

17 Wolff J. Uber die innere Architektur der knochen und ihre Bedeutung fiir die franc vom knochenwachstum. *Virchows Arch* 1870:50.

18 Smith EL, Gilligan C. Physical activity effects on bone metabolism. *Calcif Tissue Int* 1991; 49:S50–S54.

19 O'Connor JA, Lanyon LE, MacFie H. The influence of strain rate on adaptive bone remodelling. *J Biomech* 1982; 15(10):767–781.

20 Callréus M, McGuigan F, Ringsberg K, et al. Self-reported recreational exercise combining regularity and impact is necessary to maximize bone mineral density in young adult women. *Osteoporos Int* 2012; 23:2517–2526.

21 Fredericson M, Chew K, Ngo J, et al. Regional bone mineral density in male athletes: a comparison of soccer players, runners and controls. *Br J Sports Med* 2007; 41:664–668.

22 Rector RS, Rogers R, Ruebel M, et al. Lean body mass and weight-bearing activity in the prediction of bone mineral density in physically active men. *J Strength Cond Res* 2009; 23(2):427–435.

23 Duncan CS, Blimkie CJR, Cowell CT, et al. Bone mineral density in adolescent female athletes: relationship to exercise type and muscle strength. *Med Sci Sports Exerc* 2002; 34(2):286–294.

24 Rector RS, Rogers R, Ruebel M, et al. Participation in road cycling vs running is associated with lower bone mineral density in men. *Metabolism* 2008; 57:226–232.

25 Helge EW, Aagaard P, Jakobsen MD, et al. Recreational football training decreases risk factors for bone fractures in untrained premenopausal women. *Scand J Med Sci Sports* 2010; 20 Suppl 1:31–39.

26 Krustrup P, Hansen PR, Andersen LJ, et al. Long-term musculoskeletal and cardiac health effects of recreational football and running for premenopausal women. *Scand J Med Sci Sports* 2010; 20(Suppl 1):58–71.

27 Bassey, E. J., Rothwell, M. C., Littlewood, J. J., Pye DW. Pre- and postmenopausal women have different bone mineral density responses to the same high-impact exercise. *J Bone Miner Res* 1998; 13:1805–1813.

28 Snow-Harter C, Bouxsein ML, Lewis BT, et al. Effects of resistance and endurance exercise on bone mineral status of young women: a randomized exercise intervention trial. *J Bone Miner Res* 1992; 7:761–769.

29 Cavagna GA, Saibene FP, Margaria R. Mechanical work in running. *J Appl Physiol* 1964; 19(2):249–256.

30 Hill A V. The heat of shortening and the dynamic constants of muscle. *Proc R Soc London* 1938:136–195.

31 Roberts TJ, Azizi E. The series-elastic shock absorber: tendons attenuate muscle power during eccentric actions. *J Appl Physiol* 2010; 109:396–404.

32 Reeves ND, Narici M V. Behavior of human muscle fascicles during shortening and lengthening contractions in vivo. *J Appl Physiol* 2003; 95:1090–1096.

33 Lichtwark GA, Wilson AM. Is Achilles tendon compliance optimised for maximum muscle efficiency during locomotion? *J Biomech* 2007; 40:1768–1775.

34 Fukunaga T, Kubo K, Kawakami Y, et al. In vivo behaviour of human muscle tendon during walking. *Proc R Soc B* 2001; 268:229–233.

35 Lichtwark G a, Wilson AM. Optimal muscle fascicle length and tendon stiffness for maximising gastrocnemius efficiency during human walking and running. *J Theor Biol* 2008; 252(4):662–673.

36 Arampatzis A, De Monte G, Karamanidis K, et al. Influence of the muscle-tendon unit's mechanical and morphological properties on running economy. *J Exp Biol* 2006; 209:3345–3357.

37 Fletcher JR, Esau SP, MacIntosh BR. Changes in tendon stiffness and running economy in highly trained distance runners. *Eur J Appl Physiol* 2010; 110:1037–1046.

38 Buchanan CI, Marsh RL. Effects of exercise on the biomechanical, biochemical and structural properties of tendons. *Comp Biochem Physiol Part A* 2002; 133:1101–1107.

39 Albracht K, Arampatzis A. Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. *Eur J Appl Physiol* 2013; 113(6):1605–1615.

40 Kubo K, Kanehisa H, Fukunaga T. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol* 2002; 538(1):219–226.

41 Kubo K, Morimoto M, Komuro T, et al. Effects of plyometric and weight training on muscle-tendon complex and jump performance. *Med Sci Sports Exerc* 2007; 39(10):1801–1810.

42 Kubo K, Ikebukuro T, Maki A, et al. Time course of changes in the human Achilles tendon properties and metabolism during training and detraining in vivo. *Eur J Appl Physiol* 2012; 112:2679–2691.

43 Kongsgaard M, Aagaard P, Kjaer M, et al. Structural Achilles tendon properties in athletes subjected to different exercise modes and in Achilles tendon rupture patients. *J Appl Physiol* 2005; 99:1965–7191.

44 Abate M, Oliva F, Schiavone C, et al. Achilles tendinopathy in amateur runners: role of adiposity (Tendinopathies and obesity). *Muscles Ligaments Tendons J* 2012; 2(1):44–48.

45 Magnusson SP, Beyer N, Abrahamsen H, et al. Increased cross-sectional area and reduced tensile stress of the Achilles tendon in elderly compared with young women. *Journals Gerontol Ser A* 2003; 58A(2):123–127.

46 Rosager S, Aagaard P, Dyhre-Poulsen P, et al. Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scand J Med Sci Sports* 2002; 12:90–98.

47 Kubo K, Ikebukuro T, Yata H, et al. Effects of training on muscle and tendon in knee extensors and plantar flexors in vivo. *J Appl Biomech* 2010; 26:316–323.

48 Stafilidis S, Arampatzis A. Muscle - tendon unit mechanical and morphological properties and sprint performance. *J Sports Sci* 2007; 25(9):1035–1046.

49 Karamanidis K, Arampatzis A. Mechanical and morphological properties of different muscle-tendon units in the lower extremity and running mechanics: effect of aging and physical activity. *J Exp Biol* 2005; 208:3907–3923.

50 Westh E, Kongsgaard M, Bojsen-Moller J, et al. Effect of habitual exercise on the structural and mechanical properties of human tendon, in vivo, in men and women. *Scand J Med Sci Sports* 2008; 18:23–30.

51 Van Ginckel A, Thijs Y, Hesar NGZ, et al. Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: a prospective study. *Gait Posture* 2009; 29:387–391.

52 Taunton JE, Ryan MB, Clement DB, et al. A prospective study of running injuries: the Vancouver Sun Run "In Training" clinics. *Br J Sports Med* 2003; 37:239–244.

53 Cavanagh PR, Lafortune MA. Ground Reaction Forces in Distance Running*. *J Biomech* 1980; 13:397–406.

54 Selbie WS, Hamill J, Kepple TM. Three-dimensional kinetics. In: Robertson D. G. E., Caldwell G. E., Hamill J., et al., editors. *Res. methods Biomech.* 2nd ed. Champaign, Il., Human Kinetics, 2004. p. 151–176.

55 Scott S, Winter DA. Internal forces of chronic running injury sites. *Med Sci Sports Exerc* 1990; 22(3):357–369.

56 Bertelsen ML, Hulme A, Petersen J, et al. A framework for the etiology of running-related injuries. *Scand J Med Sci Sports* 2017; 38(1):42–49.

57 Lenhart RL, Thelen DG, Wille CM, et al. Increasing running step rate reduces patellofemoral joint forces. *Med Sci Sport Exerc* 2014; 46(3):557–564.

58 Teng H-L, Powers CM. Influence of trunk posture on lower extremity energetics during running. *Med Sci Sports Exerc* 2015; 47(3):625–630.

59 Almeida MO, Davis IS, Lopes AD. Biomechanical Differences of Foot-Strike Patterns During Running: A Systematic Review With Meta-analysis. *J Orthop Sport Phys Ther* 2015; 45(10):738–755.

60 Dixon SJ, Collop AC, Batt ME. Surface effects on ground reaction forces and lower extremity kinematics in running. *Med Sci Sports Exerc* 2000; 32(11):1919–1926.

61 Popp KL, McDermott W, Hughes JM, et al. Bone strength estimates relative to vertical ground reaction force discriminates women runners with stress fracture history. *Bone* 2017; 94:22–28.

62 Williams DS, Davis IM, Scholz JP, et al. High-arched runners exhibit increased leg stiffness compared to low-arched runners. *Gait Posture* 2004; 19(3):263–269.

63 Arampatzis A, Karamanidis K, Albracht K. Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude. *J Exp Biol* 2007; 210:2743–2753.

64 Maganaris CN, Paul JP. In vivo human tendon mechanical properties. *J Physiol* 1999; 521(1):307–313.

65 Komi P V, Salonen M, Järvinen M, et al. In vivo registration of Achilles tendon forces in man. I. Methodological development. *Int J Sports Med* 1987; 8(Suppl 1):3–8.

66 Fukashiro S, Komi P V, Järvinen M, et al. Comparison between the directly measured Achilles tendon force and the tendon force calculated from the ankle joint moment during vertical jumps. *Clin Biomech* 1993; 8(1):25–30.

67 Finni T, Komi P V, Lukkariniemi J. Achilles tendon loading during walking: application of a novel optic fiber technique. *Eur J Appl Physiol Occup Physiol* 1998; 77(3):289–291.

68 Sheehan FT, Drace JE. Human patellar tendon strain: a noninvasive, in vivo study. *Clin Orthop Relat Res* 2000; 370:201–207.

69 Lichtwark GA, Bougoulias K, Wilson AM. Muscle fascicle and series elastic element length changes along the length of the human gastrocnemius during walking and running. *J Biomech* 2007; 40:157–164.

70 Zernicke R, Mackay C, Lorincz C. Mechanisms of bone remodeling during weight- bearing exercise. *Appl Physiol Nutr Metab* 2006; 31:655–660.

71 Milner CE, Ferber R, Pollard CD, et al. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc* 2006; 38(2):323–328.

72 Judex S, Carlson KJ. Is bone's response to mechanical signals dominated by muscle forces? *Med Sci Sports Exerc* 2009; 41(11):2037–2043.

73 Zatsiorsky V, Seluyanov V. The mass and inertia characteristics of the main segments of the human body. In: Matsui H, Kobayashi K, editors. *Biomech. VIII-B*. Human Kinetics, Illinois, 1983. p. 1152–1159.

74 Nigg BM, Cole GK, Brüggemann GP. Impact forces during heel-toe running. *J Appl Biomech* 1995; 11(4):407–432.

75 Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. *Clin Biomech* 2011; 26:23–28.

76 Bennell K, Crossley K, Jayarajan J, et al. Ground Reaction Forces and Bone Parameters in Females with Tibial Stress Fracture. *Med Sci Sport Exerc* 2004; 36(3):397–404.

77 Nigg BM. Impact forces in running. *Curr Opin Orthop* 1997; 8(6):43–47.

78 Hennig EM, Milani TL, Lafortune MA. Use of Ground Reaction Force Parameters in Predicting

Peak Tibial Accelerations in Running. *J Appl Biomech* 1993; 9:306–314.

79 Giddings VL, Beaupré GS, Whalen RT, et al. Calcaneal loading during walking and running. *Med Sci Sport Exerc* 2000; 32(3):627–634.

80 Lieberman DE, Warrener AG, Wang J, et al. Effects of stride frequency and foot position at landing on braking force, hip torque, impact peak force and the metabolic cost of running in humans. *J Exp Biol* 2015; 218:3406–3414.

81 Heiderscheit BC, Chumanov ES, Michalski MP, et al. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc* 2011; 43(2):296–302.

82 Butler RJ, Crowell HP, Davis IM. Lower extremity stiffness: Implications for performance and injury. *Clin Biomech* 2003; 18:511–517.

83 Laughton CA, Davis IS, Hamill J. Effect of Strike Pattern and Orthotic Intervention on Tibial Shock During Running. *J Appl Biomech* 2003; 19:153–168.

84 Komi P V. Relevance of in vivo force measurements to human biomechanics. *J Biomech* 1990; 23(Suppl. 1):23–34.

85 Lyght M, Nockerts M, Kernozek TW, et al. Effects of Foot Strike and Step Frequency on Achilles Tendon Stress During Running. *J Appl Biomech* 2016; 32:365–372..

86 Bohm S, Mersmann F, Arampatzis A. Human tendon adaptation in response to mechanical loading: a systematic review and meta-analysis of exercise intervention studies on healthy adults. *Sport Med - Open* 2015; 1:1–7.

87 Hreljac A. Etiology, prevention, and early intervention of overuse injuries in runners: a biomechanical perspective. *Phys Med Rehabil Clin N Am* 2005; 16:651–667.

88 Grimston SK, Zernicke RF. Exercise-related stress responses in bone. *J Appl Biomech* 1993; 9:2–14.

89 Morgan D., Bransford DR, Costill DL, et al. Variation in the aerobic demand of running among trained and untrained subjects. *Med Sci Sport Exerc* 1995; 27(3):404–409.

90 Moore IS. Is There an Economical Running Technique? A Review of Modifiable Biomechanical Factors Affecting Running Economy. *Sport Med* 2016; 46:793–807.

91 Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech* 2007; 22:951–956.

92 Willems TM, Witvrouw E, De Cock A, et al. Gait-related risk factors for exercise-related lower-leg pain during shod running. *Med Sci Sports Exerc* 2007; 39(2):330–339.

93 Guadalupe-Grau A, Fuentes T, Guerra B, et al. Exercise and bone mass in adults. *Sport Med* 2009; 39(6):439–468.

94 Lorentzon M, Mellström D, Ohlsson C. Association of amount of physical activity with cortical bone size and trabecular volumetric BMD in young adult men: the GOOD study. *J Bone Miner Res* 2005; 20(11):1936–1943.

95 Kannus P, Józsa L, Natri A, et al. Effects of training, immobilization and remobilization on tendons. *Scand J Med Sci Sports* 1997; 7:67–71.

96 Wiesinger HP, Rieder F, Kösters A, et al. Are Sport-Specific Profiles of Tendon Stiffness and Cross-Sectional Area Determined by Structural or Functional Integrity? *PLoS One* 2016; 11(6):1–16.

97 Arampatzis A, Karamanidis K, Morey-Klapsing G, et al. Mechanical properties of the triceps surae

tendon and aponeurosis in relation to intensity of sport activity. *J Biomech* 2007; 40:1946–1952.

98 Child S, Bryant AL, Clark R a, et al. Mechanical properties of the achilles tendon aponeurosis are altered in athletes with achilles tendinopathy. *Am J Sports Med* 2010; 38(9):1885–1893.

99 Silva P, Lott R, Wickrama K a S, et al. Kinematic gait patterns in competitive and recreational runners. *J Appl Biomech* 2017; 33(4):268–276.

100 Clansey AC, Hanlon M, Wallace ES, et al. Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Med Sci Sports Exerc* 2012; 44(10):1917–1923.

101 Mizrahi J, Verbitsky O, Isakov E. Fatigue-induced changes in decline running. *Clin Biomech* 2001; 16:207–212.

102 Koblbauer IF, van Schooten KS, Verhagen E a, et al. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport* 2014; 17(4):419–424..

103 Dierks TA, Davis IS, Hamill J. The effects of running in an exerted state on lower extremity kinematics and joint timing. *J Biomech* 2010; 43:2993–2998.

104 Dierks TA, Manal KT, Hamill J, et al. Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. *Med Sci Sports Exerc* 2011; 43(4):693–700.

105 Ferber R, Noehren ATCB, Hamill J, et al. Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *J Orthop Sport Phys Ther* 2010; 40(2):52–58.

106 Willems TM, De Clercq D, Delbaere K, et al. A prospective study of gait related risk factors for exercise-related lower leg pain. *Gait Posture* 2006; 23:91–98.

107 Smock AJ, Hughes JM, Popp KL, et al. Bone volumetric density, geometry, and strength in female and male collegiate runners. *Med Sci Sports Exerc* 2009; 41(11):2026–2032.

108 Derrick TR, Dereu D, Mclean SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc* 2002; 34(6):998–1002.

109 O'Meara DM, Smith RM, Hunt AE, et al. In shoe motion of the child's foot when walking. *8th footwear Biomech. Symp.* 2007.

110 Wolf S, Simon J, Patikas D, et al. Foot motion in children shoes-A comparison of barefoot walking with shod walking in conventional and flexible shoes. *Gait Posture* 2008; 27(1):51–59.

111 Wegener C, Greene A, Burns J, et al. In-shoe multi-segment foot kinematics of children during the propulsive phase of walking and running. *Hum Mov Sci* 2015; 39:200–211.

112 Bishop C, Arnold JB, Fraysse F, et al. A method to investigate the effect of shoe-hole size on surface marker movement when describing in-shoe joint kinematics using a multi-segment foot model. *Gait Posture* 2015; 41(1):295–299.

113 Shultz R, Jenkyn T. Determining the maximum diameter for holes in the shoe without compromising shoe integrity when using a multi-segment foot model. *Med Eng Phys* 2012; 34(1):118–122.

114 Sinclair JK, Richards J, Taylor PJ, et al. 3-D kinematic comparison of treadmill and overground running. *Sport Biomech* 2013; 12:272–282.

115 Zajac FE, Neptune RR, Kautz SA. Biomechanics and muscle coordination of human walking: Part I: Introduction to concepts, power transfer, dynamics and simulations. *Gait Posture* 2002; 16:215–232.

116 Gasser JA. Assessing bone quantity by pQCT. *Bone* 1995; 17(4 SUPPL.):145S–154S.

117 Szabo KA, Webber CE, Gordon C, et al. Reproducibility of peripheral quantitative computed tomography measurements at the radius and Tibia in healthy pre- and postmenopausal women. *Can Assoc Radiol J* 2011; 62:183–189.

118 Evans RK, Negus CH, Centi AJ, et al. Peripheral QCT sector analysis reveals early exercise-induced increases in tibial bone mineral density. *J Musculoskelet Neuronal Interact* 2012; 12(3):155–164.

119 Heinemeier KM, Kjaer M. In vivo investigation of tendon responses to mechanical loading. *J Musculoskelet Neuronal Interact* 2011; 11(2):115–123.

120 Fukunaga T, Ito M, Ichinose Y, et al. Tendinous movement of a human muscle during voluntary contractions determined by real-time ultrasonography. *J Appl Physiol* 1996; 81(3):1430–1433.

121 Magnusson SP, Aagaard P, Dyhre-Poulsen P, et al. Load-displacement properties of the human triceps surae aponeurosis in vivo. *J Physiol* 2001; 531(1):277–288.

122 Kongsgaard M, Nielsen CH, Hegnsvad S, et al. Mechanical properties of the human Achilles tendon, in vivo. *Clin Biomech* 2011; 26:772–777.

123 Ito M, Akima H, Fukunaga T. In vivo moment arm determination using B-mode ultrasonography. *J Biomech* 2000; 33:215–218.

124 Maganaris CN, Baltzopoulos V, Sargeant a J. In vivo measurement-based estimations of the human Achilles tendon moment arm. *Eur J Appl Physiol* 2000; 83:363–369.

125 Fath F, Blazevich AJ, Waugh CM, et al. Direct comparison of in vivo Achilles tendon moment arms obtained from ultrasound and MR scans. *J Appl Physiol* 2010; 109:1644–1652.

126 Arampatzis A, Monte G De, Karamanidis K. Effect of joint rotation correction when measuring elongation of the gastrocnemius medialis tendon and aponeurosis. *J Electromyogr Kinesiol* 2008; 18:503–508.

127 Pataky T, Robinson M, Vanrenterghem J. Vector field statistical analysis of kinematic and force trajectories. *J Biomech* 2013; 46(14):2394–2401

CHAPTER 2: CHANGES IN RUNNING KINEMATICS AND KINETICS AFTER A 12-WEEK RUNNING PROGRAM FOR BEGINNERS

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ABSTRACT

The effect of running training on running kinematics and kinetics in novice runners has not yet been investigated. Previous studies have shown that novice runners are less economical and more prone to injury compared to well-trained runners. Since running economy (RE) and running injury risk have been associated with biomechanical variables that may be trainable, the purpose of this study was to determine the effect of a 12-week training program for beginners on the kinematics and kinetics of running. It was hypothesised that participants would evolve towards running kinematics and kinetics that have previously been associated with better RE (optimal stride frequency and length, decrease in vertical oscillation of the centre of mass, decreased leg extension at toe-off, and decreased impact, mediolateral and braking forces) and with lower injury risk (decreased hip and knee internal rotation and adduction angle, and decreased ankle pronation).

27 participants underwent a full-body, three-dimensional running analysis before and after a 12-week running program. Outcome variables included peak joint angles, joint moments, and ground reaction forces (GRF) in three planes. After training, hip external rotation moment increased significantly with 0.01 Nm/kg. Peak vertical GRF decreased with 0.9 N/kg (4.05%). There were no significant changes in peak joint angles. In conclusion, these results show that a 12-week running program for beginners that is aimed to increase running endurance does not lead to changes in running kinematics or kinetics that have previously been associated with better RE and lower injury risk.

Key words: biomechanics, training, novice runners

INTRODUCTION

Running is a feasible and time-efficient way to become physically active. Therefore, running programs for beginners have become popular over the last decades. For most participants, the aim of these programs is to increase physical fitness and to improve running performance. In order to construct training programs that are optimal for improving running performance while minimizing injury risks, it is important to understand the kinematic and kinetic adaptations that take place during a training program for beginners.

Running performance is, amongst other variables, influenced by maximal oxygen uptake (VO_2-max) and running economy (RE), which is defined as the oxygen consumption while running at a given speed. RE can be improved with a training intervention[1–3] and is therefore perceived as a 'trainable' parameter. It is known that well-trained runners have a better RE compared to untrained runners.[4–6] In addition, it has been hypothesised that through a process of self-optimization, runners develop a running gait that is most economical for them[7]. It is therefore likely that RE in novice runners will change with training.

RE is influenced by many biomechanical variables, including spatio-temporal variables, kinematics, kinetics, neuromuscular variables and storage of elastic energy. Optimal stride frequency and stride length[7], a decrease in vertical oscillation of the centre of mass[8] and decreased leg extension at toe- off[3,9], which can be achieved by a decrease in hip or knee extension, or less ankle plantar flexion, have been identified as good strategies to improve RE. Furthermore, an increased stride angle, which is defined as the angle of the parable tangent of the centre of mass at toe-off, has been associated with better RE[10]. Kinetic variables associated with better RE in experienced runners include a decrease in vertical peak impact force[9], peak medio-lateral force[9] and peak braking force[11], as well as higher propulsive force[3] and increased leg stiffness (peak vertical GRF/centre of mass displacement during contact time)[12]. If RE improves with training, these variables are likely to change as novice runners become more experienced.

A recent review study has shown that untrained runners are at more risk of developing overuse injuries compared to more experienced recreational runners.[13] Some biomechanical risk factors have been identified in the literature, which include increased hip internal rotation and adduction angle[14,15], knee internal rotation[15] and knee adduction angle, and ankle pronation.[16] These factors are possibly related to a lack in hip strength and endurance, which may increase with training. Since men are more susceptible to Achilles tendon injury and women are more susceptible to injury to the tibia, men and women may show different biomechanical risk factors and may have different responses to a 12-week running program. Therefore, sex should be taken into consideration when analysing running kinematics and kinetics before and after a training program. To our knowledge, there is no study that examines whether novice runners change their running style with training.

Longitudinal studies on changes in running biomechanics in novice runners are scarce. Moore et al.[3] found that female novice runners ran with a less extended knee and ankle at toe-off after 10 weeks of training. Furthermore, they found that after training, the ground reaction force (GRF) vector was pointed more horizontally.[17] Both variables were linked to a better running economy after training. However, Lake & Cavanagh[18] found no change in running mechanics, which may be due to the short follow-up time of 6 weeks. Bailey & Messier[19] found no change in stride length in 13 male novice runners after a 7-week training period, but stride length was the only biomechanical variable included in the study.

The aim of the present study was to study the influence of a 12-week running program on running kinematics and kinetics in novice runners. It was hypothesised that participants would adopt a running pattern that has previously been associated with lower injury risk and better running economy. Insight in the natural adaptation processes following running training will help to improve training methods and running performance, and to reduce injury risk in beginner runners.

METHODS

Participants

71 healthy participants were recruited for this study using flyers, social media and an advertisement in a local newspaper. Participants were included if they were between 18 and 60 years old, not obese (BMI below 30), and not doing any structural training in sports in the year prior to participation. Participants were excluded if they had sustained an injury to the lower limb in three months prior to participation. Participants signed informed consent prior to the first measurement. This study was approved by the ethics committee of the KU Leuven under approval number S55656.

Training program

The training program consisted of two supervised training sessions per week during 12 weeks. Participants were encouraged to do a third training session individually. Participants were allowed to choose between a training program that led from 1 to 30 minutes of continuous running, and a training program that led from 10 to 45 minutes of continuous running. Participants were instructed to run at a self-chosen, comfortable pace and were allowed to run in their own running shoes. During the training program, participants kept a log book of their training sessions. In this log book, they were also instructed to note all pains, aches and possible injuries. In case of an injury, participants informed the researchers and were referred to a sports physician.

Measurements

Participants were tested within two weeks prior to and after finishing the 12-week running program. During testing, participants wore standardised, neutral running shoes (Asics Landreth 7), provided by the researchers. 48 reflective markers were placed on anatomical landmarks of the participant's body (Figure 2.1). Markers on the feet protruded through holes in the shoes, in order to measure the motion of the feet rather than the motion of the shoes. Marker trajectories were captured at 150 Hz. The marker model included 14 body segments: trunk, pelvis, left and right upper arm, lower arm + hand, thigh, shank, rearfoot, and forefoot + midfoot. Rearfoot motion was determined using a rigid heel cluster containing three markers, attached to the heel. The longitudinal axis of the rearfoot segment runs from the ankle joint centre (defined as the middle between the two malleoli) to the middle heel cluster marker and the horizontal axis between the malleoli. Motion of the forefoot segment was defined by the markers on the navicular bone, 1^{st} metatarsal head and 5^{th} metatarsal head. This multi-segment foot model was adopted from the study of Chard et al.[20]

Figure 2.1: marker placement.

After warming up on a treadmill (5 minutes walking, two minutes jogging at 1.94 m/s and two minutes running at self-selected speed), participants were instructed to run across the floor of the lab, in which a force platform (AMTI, type OR6-7) was embedded, capturing at 900 Hz.

Data processing

For each participant, three successful trials from each test were selected for further analysis. A trial was considered successful if the participant's entire foot was within the edges of the force plate and markers were sufficiently visible during a whole stride. Events (foot strike and toe-off) on the force plate were detected based on vertical GRF with a threshold of 10 N. Marker trajectories were filtered using a 4^{th} order low-pass Butterworth filter. Joint angles and moments were calculated in Vicon Bodybuilder version 3.6.1. Joint angles and moments were calculated with respect to the proximal segment. For the foot segments specifically, the two joints of the rearfoot (the talocrural joint and the subtalar joint) were considered as one single joint with the centre located midway between the markers on the medial and lateral malleoli. The forefoot angle was defined as the angle between the midfoot + forefoot segment and the rearfoot. Joint moments were normalised to body weight. Peak joint angles and moments were calculated for each trial and averaged over the three trials using Matlab version 2014a. Other outcome variables included spatio-temporal parameters (running speed, stride length and contact time), peak GRF in three directions, loading rate and total stiffness. Instantaneous vertical loading rate (IVLR) and mean vertical loading rate (LR) were defined as the respectively the maximum and the mean slope of the vertical GRF curve between 20 and 80 percent of the interval between foot strike and impact peak.[21] Total stiffness was calculated as the peak vertical GRF divided by the vertical movement of the centre of mass during the stance phase.[22]

Statistics

One leg, being the leg with the best quality trials, per participant was included in the statistical analysis. We chose to include only one leg per participant into the analysis because there were insufficient good quality trials for both legs during the pre- and posttest. Trials were considered to be of good quality when all markers were visible during the entire stride and when the entire foot of the participant landed inside the force platform. Measuring overground running kinematics and kinetics is a time-consuming process, since the subject has to land with the entire foot on the force platform without aiming for it. Aiming for the force platform can alter stride length, therefore the participants were unaware of the location of the force platform. Therefore, many trials had to be discarded because the subject did not land on the force platform. All variables were checked for normal distribution with a Shapiro-Wilk test. Differences between the pre- and posttest were analysed using a paired t-test for the normally distributed variables and a Wilcoxon signed-rank test for the not normally distributed variables. For the variables in which an overall training effect was found, a repeated measures ANOVA was used to determine the interaction effects between training and sex to detect possible different training responses between men and women. Also, the interaction effect of training and the training program that was followed was calculated to see if there was an effect of training group on training responses. All statistical analyses were done using SPSS version 20. Alpha level was set at 0.05.

RESULTS

Out of the 71 recruited participants, 41 finished the training program. Out of these 41, only 27 participants were included in the present study due to technical problems with the force platform (Figure 2.2). There were no differences in sex, age, or weight between participants who finished the program and participants who dropped out. Participant characteristics are displayed in table 2.1.

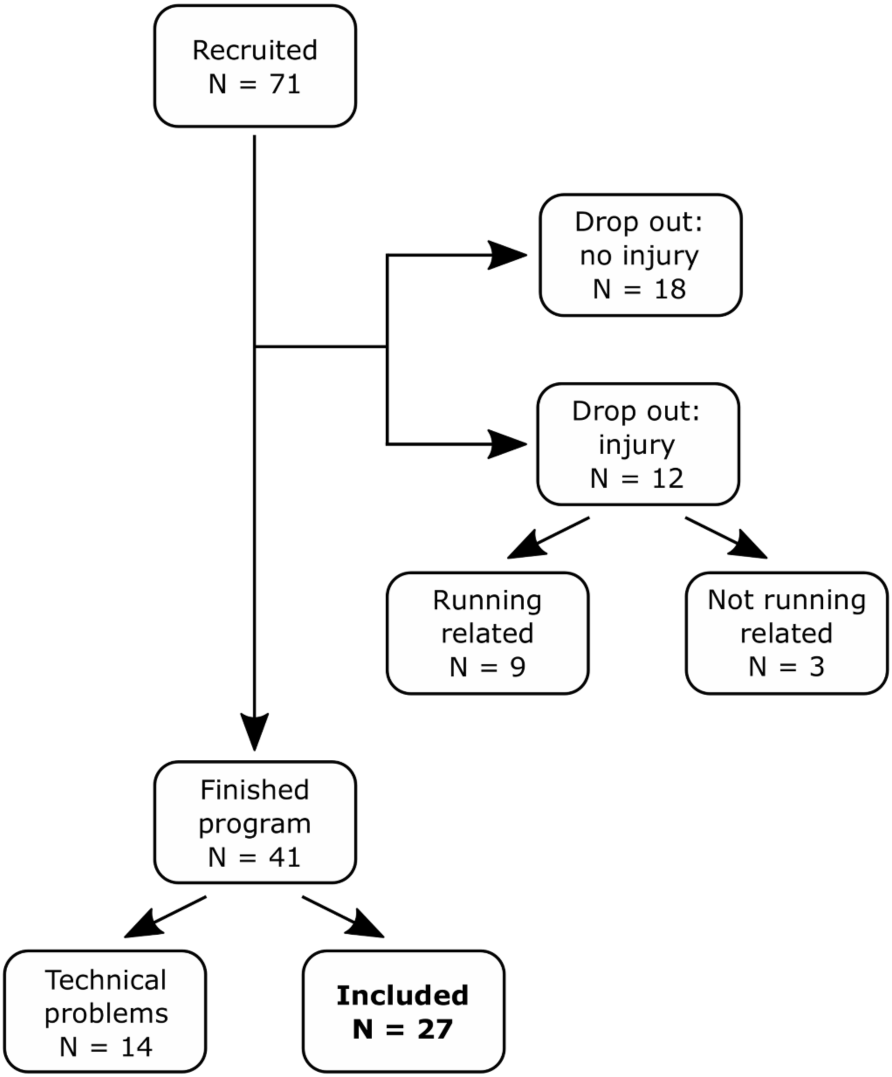

Figure 2.2: flowchart of the participants included in the study.

Sex	Age (yr)	Height (cm)	Weight pre (kg)	Weight post (kg)	Speed pre (m/s)	Speed post (m/s)
18 F; 9 M	31 ± 12	174 ± 9	70.7 ± 13.4	71.1 ± 14.0	2.87 ± 0.31	2.85 ± 0.35

Table 2.1: characteristics of the analysed participants.

Of the 27 participants, 14 chose the beginner training program, which led from 0 to 30 minutes of continuous running. Thirteen participants chose the more advanced program, leading from 10 to 45 minutes of continuous running. The older participants tended to choose the beginner program (average age 39, SD: 12 years), while the younger participants favoured the more advanced program (average age 25, SD: 7 years). On average, participants performed 27 (SD: 7) training sessions over the 12-week period. The preferred running speed did not change between the pre- and the posttest.

No changes in stride length, contact time, or centre of mass displacement were found. Changes in joint angles are shown in Table 2.2. No significant changes were found in peak joint angles after the running program (Figure 2.3). For peak joint moments, a significant increase in peak hip external rotation moment from 0.02 to 0.03 Nm/kg was found (Table 2.3). GRF in three dimensions are shown in Figure 2.4. There was no difference between pre- and posttest in medio-lateral or antero-posterior GRF. However, peak vertical GRF decreased from 23.1 (SD: 1.9) N/kg to 22.2 (SD: 1.8) N/kg (effect size = 0.52; $p < 0.001$). There was no interaction effect for time * sex or time * training program for peak vertical GRF. There were no differences in vertical impact peak, IVLR, LR, or total stiffness.

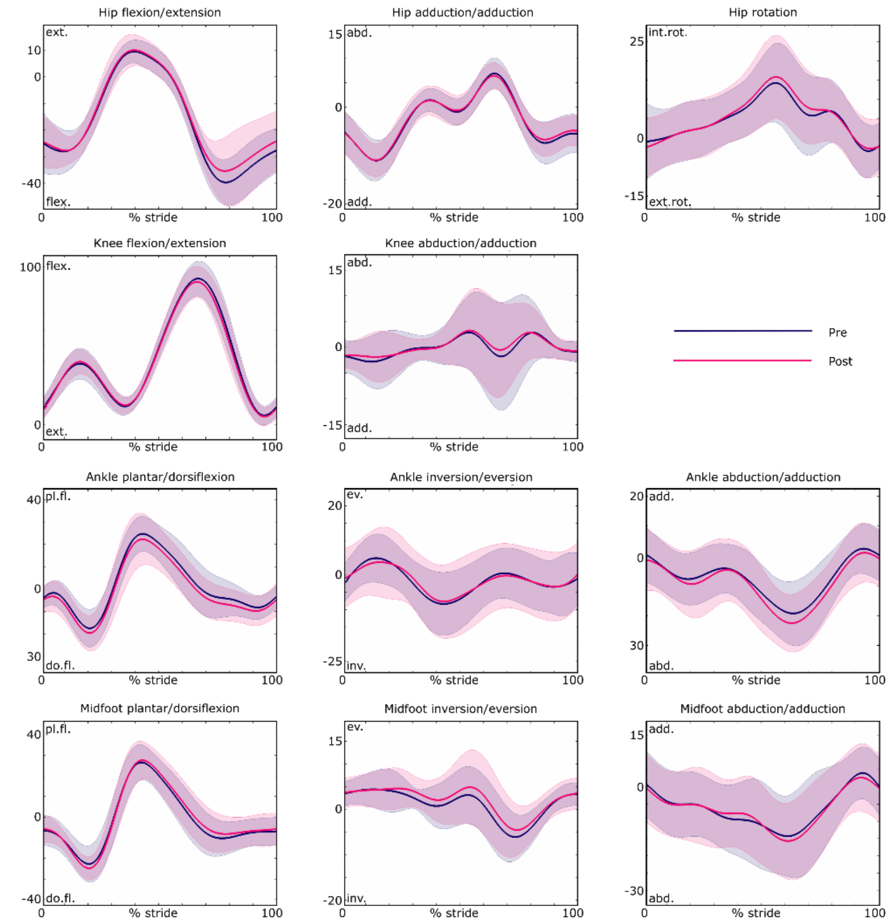

Figure 2.3: Comparison of the waveforms of joint angles [degrees] during the whole stride before (blue lines) and after (red lines) a 12-week training program for beginners. No significant changes in peak joint angles were found after training.

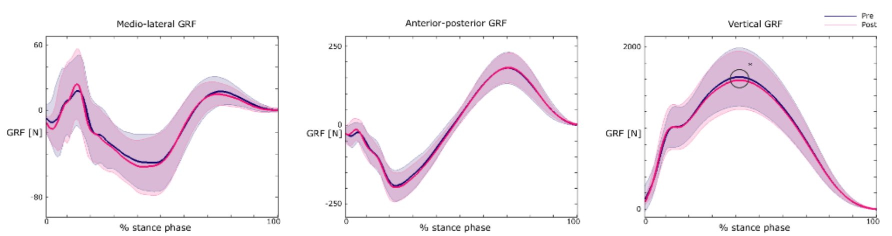

Figure 2.4: Comparison of three components of the GRF before (blue lines) and after (red lines) a 12-week running program for beginners. A significant difference (*) in peak vertical GRF after training was found.

Joint angle (°)		pre			post			change			effect size	p
Hip	flexion	40.9	±	7	38.8	±	8	-2.2	±	6	-0.36	0.075
	extension	10.1	±	4	10.5	±	6	+0.5	±	5	-0.10	0.623
	abduction	7.3	±	3	7.1	±	3	-0.2	±	3	0.07	0.708
	adduction	12.0	±	4	11.8	±	3	-0.2	±	3	-0.05	0.794
Knee	flexion	93.4	±	11	91.7	±	10	-1.6	±	8	0.21	0.296
	extension	-3.0	±	5	-2	±	6	+1.0	±	5	0.22	0.286
	abduction	7.1	±	6	7.0	±	6	-0.1	±	7	0.01	0.952
	adduction*	6.7	±	7	5.6	±	5	-1.2	±	6	-0.13	0.341
Forefoot	plantar flexion*	28.1	±	8	29.3	±	8	+1.2	±	8	-0.09	0.523
	dorsiflexion*	24.0	±	8	25.6	±	6	+1.6	±	7	-0.15	0.316
	eversion*	8.3	±	4	9.1	±	5	+0.7	±	4	-0.12	0.412
	inversion*	7.6	±	5	5.9	±	5	-1.7	±	5	-0.19	0.199
	abduction	20.8	±	12	20.1	±	10	-0.7	±	10	-0.07	0.726
	adduction*	7.2	±	8	5.9	±	7	-1.2	±	7	-0.19	0.191
Ankle	plantar flexion	26.3	±	8	24.1	±	10	-2.2	±	7	0.30	0.176
	dorsiflexion	18.4	±	8	21.2	±	8	+2.8	±	7	0.38	0.090
	eversion*	7.7	±	9	8.1	±	9	+0.3	±	8	-0.07	0.638
	inversion	11.2	±	7	12.8	±	9	+1.6	±	8	0.20	0.363
	abduction	22.2	±	10	24.1	±	9	+1.9	±	11	0.17	0.439
	adduction*	4.7	±	8	3.6	±	9	-1.1	±	8	-0.08	0.615

*Table 2.2: peak joint angles during the whole stride in degrees before and after a 12-week running program for beginners. *Non-parametric tested variable.*

Joint moments (Nm/kg)		Pre (SD)		Post (SD)		Change (SD)		effect size	p
Hip	Flexion	0.64	(0.24)	0.70	(0.18)	+0.05	(0.17)	0.32	0.108
	Extension	0.78	(0.23)	0.73	(0.24)	-0.06	(0.26)	0.21	0.276
	Abduction	1.90	(0.22)	1.87	(0.28)	-0.03	(0.24)	0.12	0.532
	Adduction	0.11	(0.12)	0.09	(0.11)	-0.02	(0.11)	-0.21	0.283
	internal rotation	0.38	(0.10)	0.38	(0.09)	+0.00	(0.10)	0.04	0.830
	external rotation	0.02	(0.02)	0.03	(0.02)	+0.01	(0.02)	-0.56	0.008**
Knee	Flexion	0.21	(0.09)	0.24	(0.08)	+0.02	(0.08)	-0.29	0.148
	Extension	2.12	(0.41)	2.18	(0.40)	+0.06	(0.37)	0.15	0.435
	Abduction	0.54	(0.27)	0.49	(0.34)	-0.05	(0.36)	0.14	0.458
	adduction*	0.08	(0.07)	0.06	(0.05)	-0.02	(0.07)	-0.13	0.353
	internal rotation*	0.04	(0.02)	0.04	(0.05)	-0.00	(0.04)	-0.05	0.694
	external rotation*	0.09	(0.07)	0.09	(0.07)	-0.00	(0.05)	-0.04	0.751
Ankle	plantar flexion	1.95	(0.29)	1.94	(0.29)	-0.01	(0.27)	0.04	0.842
	dorsiflexion*	0.16	(0.08)	0.14	(0.07)	-0.02	(0.05)	-0.22	0.113
	eversion*	0.03	(0.04)	0.04	(0.07)	+0.01	(0.07)	-0.10	0.439
	inversion*	0.26	(0.20)	0.27	(0.16)	+0.02	(0.15)	-0.11	0.400
	abduction*	0.40	(0.37)	0.33	(0.33)	-0.07	(0.30)	-0.17	0.220
	adduction*	0.12	(0.13)	0.10	(0.12)	-0.01	(0.10)	-0.10	0.493

*Table 2.3: peak joint moments in N*m/kg before and after a 12-week running program for beginners. *Non-parametric tested variable. **significant difference: $p<0.05$.*

DISCUSSION

This study aimed to determine the changes in running kinematics and kinetics after a 12-week training program for beginners. It was hypothesised that runners would change their running kinematics and kinetics towards a running style that, according to the literature, is more economical and less injury-prone.

After 12 weeks of running, no changes were observed in either of the spatio-temporal or kinematic variables. This indicates that participants did not change their stride length towards a more optimal stride length, as is suggested by Cavanagh & Williams as a strategy to improve RE[7], or that they were already at their optimal stride length at baseline. Moore et al.[3] found a decrease in knee extension and ankle plantar flexion at toe-off after a 10-week running program in 14 female beginner runners. This was suggested to be more economical because the muscles can operate at a point closer to the optimal on the force-length relationship, which causes a more efficient propulsion. These findings were not reproduced in the present study, even though the training programs were quite similar. In concordance with the present study, Lake & Cavanagh[18] did not find any changes in running kinematics after a 6-week training program. Although the variables measured in the study of Lake & Cavanagh were limited to only sagittal plane joint angles on the left side of the body, some of these (shank angle at foot strike, ankle plantar flexion angle, knee flexion angle) are associated with RE. The authors suggested that 6 weeks of training would not be sufficient to cause changes in running mechanics. The present study confirms this and suggests that even a 12-week period may be too short.

An increase in hip internal exorotator moment was found after training (Table 2.3). Excessive hip internal rotation is associated with higher injury risk[14,15]. Excessive hip internal rotation can be prevented by increasing the hip exorotator moment. However, in our participants, there was no change in the hip rotation angle after training. Therefore, the increase in hip exorotator moment did not affect the hip internal rotation angle in our sample. Furthermore, this peak external rotator moment occurred during toe-off, while the peak hip internal rotation angle (which is the risk factor) occurs during mid-stance. Therefore, we cannot conclude that this adaptation is preventive against injury risk, therefore further investigation is necessary to determine which factors lead to a decrease in injury risk as runners achieve a better training status.

A significant decrease in peak vertical GRF was found after the training program. This indicates that there is a redistribution of forces on the body after a 12-week running program: even though the differences may not be significant at joint level, they are present in the vertical GRF signal. There were no changes in the other planes, nor was there a change in GRF vector angle at peak propulsion, as was found by Moore et al.[17]. Unlike impact peak GRF, a lower peak vertical GRF is generally not associated with injury risk[23], although one cross-sectional study found a relationship between peak vertical GRF and a history of tibial and femoral neck stress fracture[24] and one study found a relationship between peak vertical GRF and history of Achilles tendinopathy[25]. These two studies are outnumbered by studies that did not find an association between injury and peak vertical GRF, so careful interpretation with regard to injury risk is necessary.

Although performance was not measured objectively, data from the log books suggested that total weekly running time increased significantly and that participants were able to run much longer distances after 12 weeks of training. This self-reporting of training data is a limitation of this study, since participants may overstate their training efforts or report them inaccurately. Another limitation of this study was that the measurements were done in a lab setting, which is different from running outside. Especially with overground running in a motion lab, the participants might not reach their usual steady training pace due to space limitation. Finally, participants were measured in standardised, neutral running shoes, while they ran in their own shoes during the training program. This may have influenced the running kinematics slightly. [26]

CONCLUSION

In conclusion, after a 12-week running program for beginners, we did not find significant changes in running kinematics or kinetics that could indicate a progression towards a more economical and less injury prone running style. This indicates that even in novice runners, running style is resistant to change when a running program designed solely to increase endurance is used. In order to change running technique in novice runners, added interventions such as strength training or technical drills may be necessary, although this remains to be further investigated.

REFERENCES

1 Beneke R, Hütler M. The effect of training on running economy and performance in recreational athletes. *Med Sci Sports Exerc* 2005; 37(10):1794–1799.

2 Gonzalez-Mohino F, Gonzalez-Rave J, Juarez D, et al. Effects of continuous and interval training on running economy, maximal aerobic speed and gait kinematics in recreational runners. *J Strength Cond Res* 2016; 30(4):1059–1066.

3 Moore IS, Jones AM, Dixon SJ. Mechanisms for improved running economy in beginner runners. *Med Sci Sports Exerc* 2012; 44(9):1756–1763.

4 Bransford DR, Howley ET. Oxygen cost of running in trained and untrained men and women. *Med Sci Sports* 1977; 9(1):41–44.

5 Morgan D., Bransford DR, Costill DL, et al. Variation in the aerobic demand of running among trained and untrained subjects. *Med Sci Sport Exerc* 1995; 27(3):404–409.

6 Saunders PU, Pyne DB, Telford RD, et al. Factors affecting running economy in trained distance runners. *Sport Med* 2004; 34(7):465–485.

7 Cavanagh PR, Williams KR. The effect of stride length variation on oxygen uptake during distance running. *Med Sci Sport Exerc* 1982; 14(1):30–35.

8 Tseh W, Caputo JL, Morgan DW. Influence of gait manipulation on running economy in female distance runners. *J Sport Sci Med* 2008; 7:91–95.

9 Williams KR, Cavanagh PR. Relationship between distance running mechanics, running economy, and performance. *J Appl Physiol* 1987; 63(3):1236–1245.

10 Santos-Concejero J, Tam N, Granados C, et al. Interaction Effects of Stride Angle and Strike Pattern on Running Economy. *Int J Sports Med* 2014; 35(13):1118–1123.

11 Kyröläinen H, Belli A, Komi P V. Biomechanical factors affecting running economy. *Med Sci Sports Exerc* 2001; 33(8):1330–1337.

12 Dalleau G, Belli A, Bourdin M, et al. The spring-mass model and the energy cost of treadmill running. *Eur J Appl Physiol* 1998; 77:257–263.

13 Videbaek S, Bueno AM, Nielsen RO, et al. Incidence of Running-Related Injuries Per 1000 h of running in Different Types of Runners: A Systematic Review and Meta-Analysis. *Sport Med* 2015; 45:1017–1026.

14 Ferber R, Noehren ATCB, Hamill J, et al. Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *J Orthop Sport Phys Ther* 2010; 40(2):52–58.

15 Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech* 2007; 22:951–956.

16 Willems TM, Witvrouw E, De Cock A, et al. Gait-related risk factors for exercise-related lower-leg pain during shod running. *Med Sci Sports Exerc* 2007; 39(2):330–339.

17 Moore IS, Jones AM, Dixon SJ. Reduced oxygen cost of running is related to alignment of the resultant GRF and leg axis vector: A pilot study. *Scand J Med Sci Sports* 2016; 26:809–815.

18 Lake MJ, Cavanagh PR. Six weeks of training does not change running mechanics or improve running. *Med Sci Sport Exerc* 1996; 28(7):860–869.

19 Bailey S, Messier S. Variations in stride length and running economy in male novice runners subsequent to a seven-week training program. *Int J Sports Med* 1991; 12(3):299–304.

20 Chard A, Greene A, Hunt A, et al. Effect of thong style flip-flops on children’s barefoot walking and jogging kinematics. *J Foot Ankle Res* 2013; 6:8.

21 Milner CE, Ferber R, Pollard CD, et al. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc* 2006; 38(2):323–328.

22 Moore IS. Is There an Economical Running Technique? A Review of Modifiable Biomechanical Factors Affecting Running Economy. *Sport Med* 2016; 46:793–807.

23 van der Worp H, Vrielink JW, Bredeweg SW. Do runners who suffer injuries have higher vertical ground reaction forces than those who remain injury-free? A systematic review and meta-analysis. *Br J Sports Med* 2016; 0:1–8.

24 Grimston SK, Engsberg JR, Kloiber R, et al. Bone mass, external Loads, and stress fracture in female runners. *Int J Sport Biomech* 1991; 7(3):293–302.

25 McCrory JL, Martin DF, Lowery RB, et al. Etiologic factors associated with Achilles tendinitis in runners. *Med Sci Sports Exerc* 1999; 31(10):1374–1381.

26 Lilley K, Stiles V, Dixon S. The influence of motion control shoes on the running gait of mature and young females. *Gait Posture* 2013; 37:331–335.

CHAPTER 3: DISTAL TIBIA GEOMETRY INCREASES IN FEMALE NOVICE RUNNERS AFTER A 12-WEEK RUNNING PROGRAM

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ABSTRACT

Running provides cyclic mechanical stresses to the bones in the lower body and therefore has a potential osteogenic effect in sedentary people. To determine the effect of a running program for beginners on tibial bone properties, tibial bone area, mass and density were measured in 11 healthy, inactive female subjects before and after a 12-week running program using peripheral quantitative computed tomography (pQCT). In order to determine the relationship between running and adaptation of the tibia, loading variables (peak vertical ground reaction force (GRFv), impact peak (IP), and loading rate (LR)) during running were associated with changes in bone geometry and density. pQCT scans of the lower legs were taken at 4%, 14% and 38% of the distal tibia length before and after the training program. Increases in bone mass (+2.0% (SD: 3.5%)) and bone area (+5.3% (SD: 11.8%)), were found in the distal tibia (4% slice). The increase in mass at 4% was positively related ($r = 0.461$, $p = 0.047$) to loading rate during running and the change in cortical area at 38% was positively related to the IP ($r = 0.489$, $p = 0.033$). In conclusion, a 12-week running program for beginners had a small but significant osteogenic effect at the distal tibia in female novice runners.

Key words: fractures, exercise, adaptation, biomechanics

INTRODUCTION

Running is an easy, affordable and time-efficient way of becoming or staying physically active. Hence, the popularity of running has increased substantially in the past decades.[1] Besides increasing aerobic fitness, cardiovascular function and running performance[2], running also provides cyclic mechanical stresses to the bones in the lower body, by applying ground reaction forces to the body and by applying muscle forces to the bones. These forces cause bone anabolism, which is necessary to maintain or increase bone strength.[3] This view is supported by studies that find a decrease in bone mass following immobilization[4], cross-sectional studies showing that athletes in sports involving weight-bearing activity, such as jumping and running, have higher bone mineral density (BMD) than inactive controls or athletes in non-weight bearing sports[5–10], and a small number of training studies.[11–14]

As running provides cyclic loading to the bones, it has the potential to maintain or enhance bone strength. Bone weakness, as reflected by decreased BMD and bone mass, increases the risk of stress fractures.[15] Inactivity or even immobilization following injury further decreases loading of the bones, thereby decreasing bone strength even more. Therefore, an active lifestyle, including activities that involve bone loading, such as running, jumping and strength training, is necessary to maintain bone health and to prevent injury.

Various cross-sectional studies have found that runners have higher BMD than sedentary people.[5,6,9,10,16] BMD in the legs of runners was 3.3 – 8.5% higher compared to inactive subjects or subjects doing non-impact sports. Along with BMD, bone cross-sectional area and the distribution of bone mass in the bone reflect bone strength. Together, these parameters define the bone's ability to resist bending and torsional forces.[17] The difference in geometrical properties of the bone between runners and non-runners was even higher: 3.4-17.6% difference was found in cross-sectional area of the tibia, while a difference of 8.1-28.1% in cortical area was found.[18,19] These findings indicate that bones in the legs adapt to habitual running and that these adaptations are larger in geometrical parameters compared to BMD. However, the short-term effect of running training on tibial bone properties is unknown.

Longitudinal studies that studied the effect of running on bone strength with a training intervention are scarce.[11,12,14,20] Results show that these training interventions are mostly successful in increasing BMD. Snow-Harter et al.[14] found a small but significant increase in lumbar BMD. Martin et al.[20] found no change in BMD after a running intervention, but their population consisted of post-menopausal women, in which a decline in BMD is normally expected. Helge et al.[11] found a small increase in distal tibia BMD of 0.7% (left leg) and 1.1% (right leg), that was only significant in the right leg, in a population of inactive, premenopausal women after 14 weeks of endurance running. Krustrup et al.[12] found that leg BMD increased with running training, but not until after 16 months of training. In the studies of Helge et al.[11] and Krustrup et al.[12], running training was compared to football training. The latter yielded larger improvements in BMD, possibly because football involves jumping and sprinting, causing larger accelerations and therefore larger bone loading than running.

Of the four training studies, only Helge et al.[11] used peripheral quantitative computed tomography (pQCT) to evaluate bone strength, which has the benefit of being able to detect changes in bone geometry in addition to BMD. Stronger bones are characterized by high BMD, high cross-sectional area, and high moments of inertia[21]. Increased cortical BMD, as was found by Helge et al.[11] after training, leads to higher resistance against bending and torsion forces, and is therefore an important measure of bone strength.

The findings of Helge et al.[11] indicate that an improvement in BMD can already be achieved after 14 weeks of running training, which is close to the duration of typical running programs for beginners, leading from zero to 30 minutes of running. These programs are very popular because they are time-efficient and, unlike football and strength training, can be done anywhere at any time. Therefore, the first aim of this study was to determine the short-term effects of a typical, popular 12-week running program on tibial geometry and density parameters using pQCT. The finding that football training yields larger increases in BMD than endurance running training[11,12], indicates that the magnitude of loading may influence the response of BMD to training. Ground reaction forces reflect the magnitude of the bone loading during running. Therefore, the second aim of this study was to relate loading parameters, including peak GRFv, impact peak and loading rate, to change in bone properties. We hypothesised that 12 weeks of running training would invoke an osteogenic response in healthy, inactive female participants and that loading parameters are positively correlated to increase in bone density and geometry. Because women have lower baseline BMD values compared to men[22] and women are at higher risk of loss of bone mass[23] and injury to the tibia[24], only female participants were included in the analyses. We hypothesized that geometric parameters (total area and cortical area) would increase more compared to bone density parameters. To our knowledge, this is the first study to relate bone loading during running to change in bone properties over the course of a short term running program for beginner runners.

MATERIALS AND METHODS

27 healthy, female volunteers participated in this study. Sample size was calculated using the findings of Smock et al.[19], who found a difference in total bone area at 4% from the distal tibia between female runners (967.0 ± 98.4) and inactive controls (868.9 ± 97.9). A power analysis with an alpha level of 0.05 and a beta of 0.2 yielded a required sample size of 16. To meet eligibility criteria, participants had to be over 18 years old, not obese (BMI < 30), inactive (not participating in any kind of structural physical training for at least one year), injury-free for at least three months, and pre-menopausal (self-administered). Participants signed informed consent before the first measurement. This study was approved by the local ethics committee under approval number S55656.

The training program consisted of 12 weeks of running training. There were two supervised training sessions per week, and participants were encouraged to perform a third training session individually. To keep participants motivated, they were allowed to choose between two training programs: one that led from 1 to 30 minutes of continuous running and one that led from 10 to 45 minutes of continuous running. Both programs alternated running with short walking intervals. Participants were instructed to run at a comfortable pace and to use their own running shoes. Participants kept a log book in which they noted their training sessions, as well as any injuries. In case of a running-related injury, participants informed the researchers after which they were referred to a sports physician.

Before and after the running program, subjects underwent a three-dimensional running analysis at the Movement and posture Analysis Laboratory Leuven and a pQCT scan (XCT-2000, Stratec, Germany) of the lower legs at the University Hospital Leuven. During the running analysis, subjects warmed up on a treadmill before they ran back and forth across the floor of the motion lab at a self-selected, comfortable pace. A force platform (AMTI, type OR6-7), capturing at 900 Hz, was embedded in the floor of the motion lab. Three trials of each foot per participant were selected for processing. From the unfiltered (GRFv) signal, vertical impact peaks (IP) and peak GRFv were extracted. If there was no vertical IP in the GRFv signal, as was the case in 33% of the steps, the GRFv at 13% of the stance phase was taken as a surrogate measure of IP[25]. Peak vertical loading rates (LR) and instantaneous vertical loading rates (IVLR) were calculated as the peak and mean slope of the GRFv between 20 and 80 % of the interval between foot strike and IP[26]. Loading parameters (IP, LR, IVLR and GRFv) were normalised to body weight. All calculations were done in Matlab version R2014a.

The pQCT scans were taken in the Centre for bone densitometry in the University Hospital Leuven. Scans of the lower legs were taken at 4, 14 and 38% of the distal tibia length (Figure 3.1), in accordance with the protocol from Wilks et al.[27] Tibia length was measured manually, between the medial malleolus and the proximal edge of the medial tibial plateau. In the tibia, the 4% site is typically used to analyse trabecular bone characteristics, while the 14% and 38% slices are often used to analyse cortical bone characteristics.[27,28] Scans were always taken by the same researcher and on the same device. From these scans, the following parameters were calculated: mass, area, density, trabecular density, cortical area, and cortical density (Table 3.1). Bone parameter values that fell outside plus or minus three standard deviations from the mean were considered outliers and were removed (14 out of a total of 704 data points).

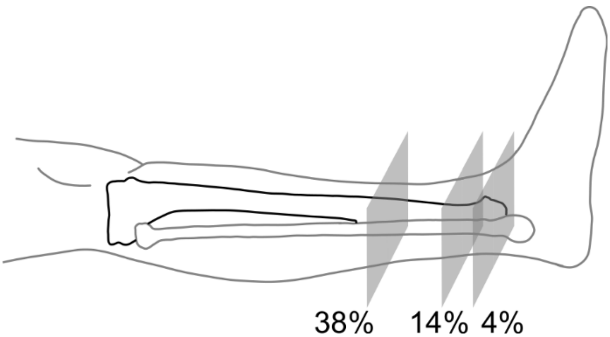

Figure 3.1: pQCT scans were taken at 4%, 14% and 38% of the tibia length.

Measure	**Description**	**Unit**	**Slice**
Mass	Mass of 1-cm thick slice	g	4%, 14%, 38%
Area	Area of slice	mm^2	4%, 14%, 38%
Density	Density of slice	mg/cm^3	4%
Trabecular density	Density of trabecular bone	mg/cm^3	4%
Cortical area	Area of cortical bone	mm^2	14%, 38%
Cortical density	Density of cortical bone	mg/cm^3	14%, 38%

Table 3.1: variables calculated from the pQCT scans

Statistical analyses were performed using SPSS (SPSS Statistics 22, IBM Corporation, United States). Outcome variables were checked for normal distribution using a Kolmogorov-Smirnov test. Since all data were normally distributed, parametric testing was performed. Changes after the running program were analysed using a repeated measures ANOVA with bone parameters as dependent variables and training program as a factor. For each subject, the legs were taken into account independently in the analysis. Although the left and right leg belong to the same subject, both loading and adaptation can differ substantially between the left and the right leg. Two-tailed Pearson correlation coefficients were calculated between changes in outcome variables and loading parameters (IP, peak GRFv, LR and IVLR). Correlations were not corrected for multiple testing, since different adaptations are expected at different sites. At the 4% site, trabecular bone properties are measured, whereas at the 14 and 38% sites, cortical bone properties are measured. In addition, there could be different local strains in these areas during running.

RESULTS

27 female novice runners were included in the baseline measurements. 10 participants dropped out of the training program: 3 participants dropped out due to

injury; 7 participants dropped out due to lack of time or lack of motivation. Due to logistic and technical problems, 6 participants completed the training, but failed to complete the posttests. 11 participants completed the training program and 12-week measurements. Participant characteristics are displayed in Table 3.2. Four subjects participated in the beginner program (0-30 min) and seven subjects chose the more advanced program (10-45 min).

	N	Age (yr)	Height (cm)	Weight (kg)	Completed sessions
Participants	11	27 ± 7	169 ± 7	63 ± 9	29 ± 2

Table 3.2: subject characteristics

Participants showed significant increases in total mass (+1.9 %, SD: 3.5) and total area (+5.3 %, SD: 11.8) at the 4% slice, and in cortical density (+0.6%) at the 38% slice (Table 3.3). There were no interaction effects between training and program, indicating that participants who followed the beginner program did not respond differently from participants who followed the more advanced program.

	Mean pre (SD)	Mean post (SD)	% change	p	Effect size (η^2)
Total mass at 4% (g)	3.15 (0.37)	3.21 (0.38)	+1.9	0.015*	0.26
Total area at 4% (mm²)	994 (116)	1047 (126)	+5.3	0.047*	0.17
Total density at 4% (mg/cm³)	313 (41)	311 (42)	-0.6	0.564	0.018
Trabecular density at 4% (mg/cm³)	240 (37)	241 (39)	+0.4	0.410	0.08
Total mass at 14% (g)	2.42 (0.31)	2.41 (0.30)	-0.4	0.607	<0.00
Total area at 14% (mm²)	438 (57)	443 (57)	+1.1	0.127	0.12
Cortical area at 14% (mm²)	163 (25)	161 (24)	-1.2	0.222	0.08
Cortical density at 14% (mg/cm³)	1139 (17)	1136 (19)	-0.3	0.076	0.16
Total mass at 38% (g)	3.55 (0.50)	3.55 (0.46)	0.0	0.772	<0.00
Total area at 38% (mm²)	396 (55)	398 (61)	+0.5	0.706	0.01
Cortical area at 38% (mm²)	279 (41)	276 (35)	-1.1	0.256	0.06
Cortical density at 38% (mg/cm³)	1180 (21)	1187 (19)	+0.6	0.049*	0.19

Table 3.3: bone parameters before and after the 12-week running program.

Two significant correlations between loading variables and changes in bone parameters were found: LR during running was positively correlated to increase in mass at 4% ($r = 0.461$, $p = 0.047$) and IP was positively correlated to change in cortical area at 38% ($r = 0.489$, $p = 0.033$), indicating that higher bone loading leads to larger increases in these bone parameters.

DISCUSSION

The first aim of the present study was to determine the effects of a 12-week running program for beginners on bone area, mass and density of the tibia in female novice runners. We hypothesised that the training program would have an osteogenic effect, leading to an increase in total and cortical area.

The results from the pQCT scans provided partial support for this hypothesis. Increases of 2.0% in mass and 5.3% in area of the distal tibia (at 4% of tibia length), and 0.6% in cortical density at 38% of tibia length were found, indicating an osteogenic effect of the training program in female novice runners. Szabo et al.[29] tested the reproducibility of the XCT-2000 pQCT scanner in the distal tibia (4 and 38% of tibia length) in 30 women. The authors reported a variability (root mean square of variation) of 1.6% for tibia mass and a variability of 2.8% in tibial area at 4% tibial length. The significant changes in tibia mass and area found in our sample are both larger than the variability reported by Szabo et al.[29] The results partially supported our second hypothesis that area would change rather than bone density: total area of the 4% slice of the distal tibia increased, whereas cortical area remained the same.

Two previous studies measured tibial bone properties before and after a running program using pQCT[11,28]. Evans et al.[28] found a significant 1.2% increase in trabecular density at 4% of tibia length, as well as a significant increase of 1.2% in total area at 38% of tibia length in a group of 14 young (age 20, SD: 2 years) women after only 8 weeks of running training. In the present study, we found no changes in these two variables. Helge et al.[11] found no significant changes after 14 weeks of running in a group of 16 pre-menopausal women (age 37, SD: 8 years). In comparison with these previous studies, the present study yielded promising results, with increases of 2% in total mass and 5.3% in total area in the distal tibia.

The second aim of this study was to associate loading parameters to changes in bone parameters. Our results indicate that high IP and peak LR during running are associated with higher increases in some of the bone parameters (mass at 4% and cortical area at 38%), which supports our hypothesis. However, there seems to be a fine balance between bone loading and overloading: high bone strains caused by high IP and LR are necessary to invoke bone adaptation, while those very same factors are associated with development of overuse injury[26]. In our subject group, none of the participants developed overuse injuries to the lower legs, indicating that the loading in this particular training program was below the loading capacity of the tibia.

There are several limitations to this study. The first limitation to this study was the absence of a control group or control site, to which the changes in bone parameters in the experimental group could have been compared. Changes in bone density and geometry could have been compared to changes in a group of healthy volunteers who did not undergo a running program or to changes in bone properties of another site that is less likely to be affected by running, such as the radius. However, it can be assumed that in healthy, inactive people (especially in women[30]), bone strength will be in a steady state. None of the training studies on running and bone properties found significant changes in the bone properties of their control groups[11,12,14,20]. Therefore, if increases in bone strength are found, they are likely to be caused by the intervention rather than by natural history of bone changes. Furthermore, a previous study has found that pQCT scans, made with the same type of scanner used in our study, have good reproducibility.[29]

A second limitation, which also affects all the other cited training studies[11,12,14,20], is the difficulty to quantify the cumulative loading on the bones of the subjects. We only have objective information on the subjects' activities during the training hours, while their physical activity outside training hours and their exercise habits in the years/decades prior to participation in the study may influence their training response. Differences in historical training volume and intensity may explain the large variation in training response. Third, due to high drop-out rates during the running program and poor compliance with the study procedures, sample size was lower than the calculated required sample size of 16 and the power of the results is therefore lower than intended. Since bone strength is dependent on age, the sample may have been too heterogeneous, which could explain the large standard deviations. Future studies should focus on studying the effect of running on bone properties in larger, homogeneous samples with regard to age, while paying attention to objective tracking of training volume and intensity. Finally, loading parameters during running were measured in a lab environment, which may be different from a real-life running environment. In particular, the fact that participants were running on a 12m runway may alter GRF characteristics because it is very difficult to reach a constant speed within 6m, which is the distance from the starting point to the force platform.

PERSPECTIVE

Running is a very popular exercise mode for improving cardiovascular health and fitness, but because of the associated forces on the bones of the lower limb, it may also have osteogenic benefits. Therefore, this study aimed to determine the effects of a 12-week running program for beginners on bone properties of the tibia. Results indicated that even a relatively short training intervention of 12 weeks of running training was beneficial for tibial bone properties in inactive females. Therefore, running may be recommended for healthy individuals to increase or maintain bone strength, thereby preventing problems associated with loss of bone mass later in life.

REFERENCES

1 Running USA. *2013 national runner survey*. 2013.

2 Oja P, Titze S, Kokko S, et al. Health benefits of different sport disciplines for adults: systematic review of observational and intervention studies with meta-analysis. *Br J Sports Med* 2015; 49:434–440.

3 Bonewald LF, Johnson ML. Osteocytes, mechanosensing and Wnt signaling. *Bone* 2008; 42:606–615.

4 Parry SM, Puthucheary ZA. The impact of extended bed rest on the musculoskeletal system in the critical care environment. *Extrem Physiol Med* 2015; 4:16.

5 Callréus M, McGuigan F, Ringsberg K, et al. Self-reported recreational exercise combining regularity and impact is necessary to maximize bone mineral density in young adult women. *Osteoporos Int* 2012; 23:2517–2526.

6 Fredericson M, Chew K, Ngo J, et al. Regional bone mineral density in male athletes: a comparison of soccer players, runners and controls. *Br J Sports Med* 2007; 41:664–668.

7 Lorentzon M, Mellström D, Ohlsson C. Association of amount of physical activity with cortical bone size and trabecular volumetric BMD in young adult men: the GOOD study. *J Bone Miner Res* 2005; 20(11):1936–1943.

8 Rantalainen T, Nikander R, Heinonen A, et al. Direction-specific diaphyseal geometry and mineral mass distribution of tibia and fibula: a pQCT study of female athletes representing different exercise loading types. *Calcif Tissue Int* 2010; 86:447–454.

9 Rector RS, Rogers R, Ruebel M, et al. Lean body mass and weight-bearing activity in the prediction of bone mineral density in physically active men. *J Strength Cond Res* 2009; 23(2):427–435.

10 Duncan CS, Blimkie CJR, Cowell CT, et al. Bone mineral density in adolescent female athletes: relationship to exercise type and muscle strength. *Med Sci Sports Exerc* 2002; 34(2):286–294.

11 Helge EW, Aagaard P, Jakobsen MD, et al. Recreational football training decreases risk factors for bone fractures in untrained premenopausal women. *Scand J Med Sci Sports* 2010; 20 Suppl 1:31–39.

12 Krustrup P, Hansen PR, Andersen LJ, et al. Long-term musculoskeletal and cardiac health effects of recreational football and running for premenopausal women. *Scand J Med Sci Sports* 2010; 20(Suppl 1):58–71..

13 Bassey, E. J., Rothwell, M. C., Littlewood, J. J., Pye DW. Pre- and postmenopausal women have different bone mineral density responses to the same high-impact exercise. *J Bone Miner Res* 1998; 13:1805–1813.

14 Snow-Harter C, Bouxsein ML, Lewis BT, et al. Effects of resistance and endurance exercise on bone mineral status of young women: a randomized exercise intervention trial. *J Bone Miner Res* 1992; 7:761–769.

15 Davey T, Lanham-New SA, Shaw AM, et al. Fundamental differences in axial and appendicular bone density in stress fractured and uninjured Royal Marine recruits - A matched case-control study. *Bone* 2015; 73:120–126.

16 Rector RS, Rogers R, Ruebel M, et al. Participation in road cycling vs running is associated with lower bone mineral density in men. *Metabolism* 2008; 57:226–232.

17 Burr D. The relationships among physical, geometrical and mechanical properties of bone, with a note on the properties of nonhuman primate bone. *Yearb Phys Anthropol* 1980; 23:109–146.

18 Nikander R, Kannus P, Rantalainen T, et al. Cross-sectional geometry of weight-bearing tibia in female athletes subjected to different exercise loadings. *Osteoporos Int* 2010; 21(10):1687–1694.

19 Smock AJ, Hughes JM, Popp KL, et al. Bone volumetric density, geometry, and strength in female and male collegiate runners. *Med Sci Sports Exerc* 2009; 41(11):2026–2032.

20 Martin D, Notelovitz M. Effects of aerobic training on bone mineral density of postmenopausal women. *J Bone Miner Res* 1993; 8(8):931–936.

21 Cheng S, Toivanen JA, Suominen H, et al. Estimation of structural and geometrical properties of cortical bone by computerized tomography in 78-year-old women. *J Bone Miner Res* 2009; 10(1):139–148.

22 Burghardt AJ, Kazakia GJ, Ramachandran S, et al. Age- and gender-related differences in the geometric properties and biomechanical significance of intracortical porosity in the distal radius and tibia. *J Bone Miner Res* 2010; 25(5):983–993.

23 Guadalupe-Grau A, Fuentes T, Guerra B, et al. Exercise and bone mass in adults. *Sport Med* 2009; 39(6):439–468.

24 Brunet ME, Cook SD, Brinker MR, et al. A survey of running injuries in 1505 competitive and recreational runners. *J Sport Med Phys Fit* 1990; 30(3):307–315.

25 Blackmore T, Willy RW, Creaby MW. The high frequency component of the vertical ground reaction force is a valid surrogate measure of the impact peak. *J Biomech* 2016; 49:479–483.

26 Milner CE, Ferber R, Pollard CD, et al. Biomechanical factors associated with tibial stress fracture in female runners. *Med Sci Sports Exerc* 2006; 38(2):323–328.

27 Wilks DC, Winwood K, Gilliver SF, et al. Age-dependency in bone mass and geometry: A pQCT study on male and female master sprinters, middle and long distance runners, race-walkers and sedentary people. *J Musculoskelet Neuronal Interact* 2009; 9(4):236–246.

28 Evans RK, Negus CH, Centi AJ, et al. Peripheral QCT sector analysis reveals early exercise-induced increases in tibial bone mineral density. *J Musculoskelet Neuronal Interact* 2012; 12(3):155–164.

29 Szabo KA, Webber CE, Gordon C, et al. Reproducibility of peripheral quantitative computed tomography measurements at the radius and Tibia in healthy pre- and postmenopausal women. *Can Assoc Radiol J* 2011; 62:183–189.

30 Leitao de Azevedo MN, Nunes JV, Pasqualette HA, et al. Bone Mineral Density at 45 Years of Age, Before Menopause. *J Natl Med Assoc* 2009; 101(8):788–792.

CHAPTER 4: ACHILLES TENDON ADAPTATION AND ACHILLES TENDINOPATHY IN RUNNING: A NARRATIVE REVIEW

E Maas[1], I Jonkers[1], K Peers[2], B Vanwanseele[1]

Maas, E, Jonkers, I, Peers, K, Vanwanseele B. (2013). Achilles tendon adaptation and Achilles tendinopathy in running. OA Orthopaedics 1 (3): 25-30.

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ABSTRACT

Introduction

Achilles tendinopathy is a common overuse injury in runners and related to maladaptation of the Achilles tendon. The aim of the present review is to provide an overview of the literature on the adaptation of the Achilles tendon to running and the maladaptation caused by overloading of the tendon that leads to Achilles tendinopathy.

Results

Cross-sectional studies reveal that runners have thicker Achilles tendons than non-runners, but no difference in its stiffness is found. Patients with Achilles tendinopathy have a larger Achilles tendon cross-sectional area, but lower stiffness than those of healthy people. Longitudinal studies on the adaptation of Achilles tendon mechanical properties are scarce and do not find a change in Achilles tendon size or stiffness.

Conclusion

More longitudinal studies are necessary to find out what magnitude of strain is needed to trigger an adaptational response in tendons and to define a threshold between loading and overloading of the Achilles tendon.

INTRODUCTION

The Achilles tendon is one of the most injured tendons in the human body. Especially, runners are at high risk of injuring their Achilles tendons: 8% of novice runners develop Achilles tendinopathy[1] and 56% of elite runners report to have suffered from Achilles tendinopathy at some point in their career.[2] Achilles tendinopathy is defined as a combination of pain in the Achilles tendon area, swelling and impaired performance.[3] The exact injury mechanism for Achilles tendinopathy is currently unknown.

Similar to other musculoskeletal tissues, the Achilles tendon responds to mechanical loading with structural adaptations that make the tendon stronger and more resistant to strain.[4,5] Although a certain level of strain is required for these adaptations, it has been suggested that too high strains will overload the tendon and cause microdamage.[6] Following exercise, collagen synthesis is enhanced.[7] Simultaneously, the degradation of collagen protein also increases, outweighing the collagen synthesis[8] (Figure 4.1). In the 18–36 h after exercise, there is a negative net balance in collagen levels (catabolic state so loss of collagen), which after 36 h turns positive up to 72 h after exercise (anabolic state so regeneration of collagen).[6] These data suggest that apart from the level of strain, sufficient rest between training sessions needs to be respected in order to reduce the net loss of collagen content, which may lead to tendon injury. It therefore seems that there is a subtle balance between loading and overloading a tendon, depending on several factors including training volume, type of loading and recovery time.[6]

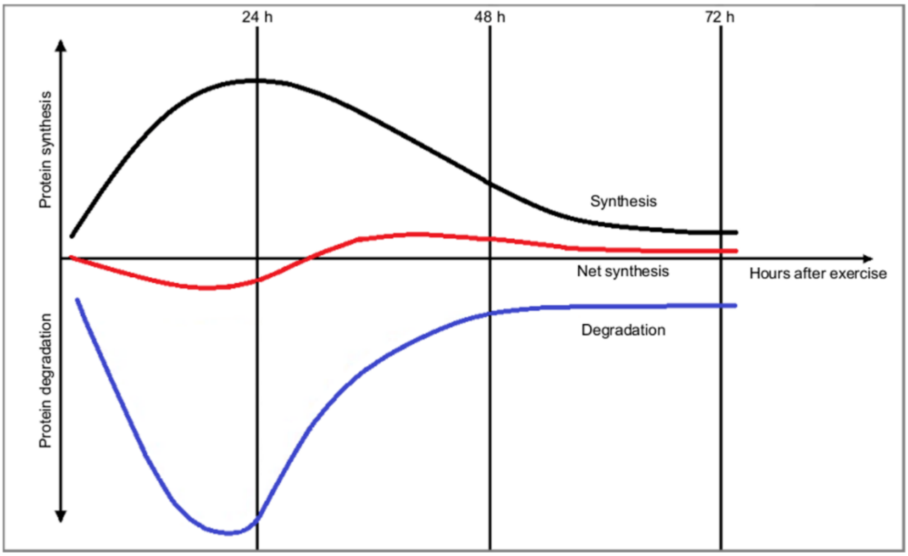

Figure 4.1 (adapted from Magnusson et al.(6)): protein synthesis and degradation after a bout of exercise.

The purpose of the present review is to provide an overview of the healthy adaptation mechanisms of Achilles tendon to running and on the other hand, maladaptations caused by overloading of the tendon that lead to Achilles tendinopathy. These insights will be discussed in the context of training recommendations for injury-free running.

RESULTS

Adaptation of tendon to running

To evaluate the adaptations of the Achilles tendon to running, a number of studies compared the mechanical properties of Achilles tendons of runners with those of non-runners. Achilles tendon stiffness can be measured during isometric plantar flexion contractions during which tendon elongation is measured using ultrasonography. Tendon stiffness is then defined as the slope of the force/elongation relationship.[9] Achilles tendon's cross-sectional area (CSA) can be measured from MRI scans or ultrasonograms.[9] The findings of these studies are summarised in Table 4.1.

Study	Design	Exp. group	Contr. group	Findings
Abate et al.[10]	CS	21 runners; 25 overweight runners	16 non-runners; 19 overweight non-runners	AT thickness (midportion) was greater in runners than in non-runners. Overweight people had more sonographic abnormalities than non-overweight people. Overweight runners had more sonographic abnormalities than non-overweight runners
Arampatzis et al.[11]	CS	28 male sprinters; 28 male endurance runners	10 non-active male controls	No significant difference in AT stiffness between long distance runners and controls; stiffness in sprinters was larger than in long distance runners and controls
Hansen et al.[9]	Long	11 untrained subjects (7male, 4female)	-	After 32-week running intervention: no change in AT CSA; no change in plantar flexor moment, no change in corresponding tendon-aponeurosis displacement; insignificant increase in tendon stiffness
Kongsgaard et al.[7]	CS	8 male elite long distance runners 6 male AT rupture patients (avg 1.2years post-surgery)	9 male elite kayakers	AT CSA of runners > kayakers AT CSA of runners > AT rupture subjects
Kubo et al.[8]	CS	15 male long distance runners	21 untrained subjects	Relative AT thickness (to body mass) of LD runners >controls, no difference in absolute AT thickness. No difference in AT stiffness

Magnusson and Kjaer[12]	CS	6 male long distance runners	6 male non-runners	Runners have greater AT CSA than non-runners in the distal, but not the proximal part of the tendon
Rosager et al.[13]	CS	5 male runners	5 male untrained	AT CSA of runners > non-runners; no difference in stiffness and stress/strain relationship
Westh et al.[14]	CS	10 female runners, 10 male runners	10 female non-runners	No difference in normalised AT CSA between female runners and non-runners. Male runners AT CSA > female runners

Table 4.1: Achilles tendon properties in runners versus non-runners. AT = Achilles tendon, CS = cross-sectional study design, CSA = cross-sectional area, LD = long distance.

It has been found that collagen turnover is increased after a bout of running[15], suggesting that running causes tendon hypertrophy. Indeed, six out of seven studies found a larger Achilles tendon CSA in runners compared with non-runners[7,8,11–13], although sometimes this difference was only present in specific parts of the Achilles tendon[7,12] or only if the Achilles tendon CSA was normalised to body weight.[8] Other studies examining the effect of a (non-running) training programme on tendon size and stiffness also found that tendon hypertrophy following training is region specific.[16] This may be due to the difference in loading of different parts of the Achilles tendon: the distal part of the tendon is not only subject to tensile loads but also to compressive loads caused by the compression of the space between the distal part of the tendon and the calcaneus during dorsiflexion.[12]

Only one out of four studies found a difference in tendon stiffness between runners and non-runners.[11] More specifically, sprinters had larger tendon stiffness compared with long distance runners and non-runners. There was no difference in tendon stiffness between long distance runners and non-runners. This suggests that the strain imposed on the Achilles tendon by submaximal running is not sufficient to trigger adaptation responses, whereas sprint training does generate such responses. CSA was not measured in this study, so it cannot be concluded whether the larger stiffness in sprinters was due to tendon hypertrophy or architectural changes. Theoretically, tendon stiffness is directly related to tendon CSA, but this is not consistently reflected in the results from the studies in Table 4.1. Rosager et al.[13] found larger Achilles tendon CSA in runners compared with controls, but no difference in tendon stiffness. Kubo et al.[8] and Hansen et al.[9] found no difference in both absolute CSA and tendon stiffness between runners and controls.

Tendon properties, loading and adaptations are gender specific. Only one study included in Table 4.1 examined the Achilles tendon properties of female runners versus female non-runners and did not find a difference in CSA.[14] Moreover, the difference in CSA between various portions of the Achilles tendon was much larger in men than in women (in male runners, the CSA of the distal part of the tendon was 75% larger than the proximal part, compared with 11% in female runners), indicating that the region-specific adaptation of Achilles tendon may be gender specific. Interestingly, injuries to the Achilles tendon occur more frequently in men than in women. This could be due to a larger plantar flexor moment arm in men, which causes more strain on the Achilles tendon for a given change in joint angle.[17] Since tendon adaptation has also been linked to oestrogen levels[14] and collagen synthesis is found to be lower in women compared with men, and rises less after exercise[18], it is not surprising that tendon adaptation is gender specific. Thus, more research is needed to find effects of running on mechanical properties of tendon in women.

To see the course of tendon adaptation to a running programme and in order to find out mechanisms behind Achilles tendinopathy, it is necessary to do longitudinal follow-up studies. Yet, the majority of the studies on the effects of running on mechanical properties of the Achilles tendon have a cross-sectional design, comparing runners with non-runners. With this study design, it is impossible to detect cause–effect relationships between running and the outcome variables. Changes in mechanical properties could be not only due to the running programme but also to the subject-specific running style, pre-existing conditions or other variables. Only one longitudinal study on the effects of a running programme on tendon mechanical properties could be found.[9] No changes in tendon CSA and tendon stiffness were found after 32 weeks of running. It should be noted that this study had a relatively small sample size (N=11) and included both men and women. Therefore, it may be possible that no differences in tendon size and stiffness were found because tendon adaptations are gender specific. It could also be that it takes more time for the tendon to adapt than the 32-week running programme that was administered in this study. Yet, since there was an insignificant increase in tendon stiffness of 5%–7%, it could be possible that a difference would be found in a larger sample (N=11). Several of the studies presented in Table 4.1 suffer from small sample size (e.g. of Rosager et al.).[13]

Mechanical and structural properties of tendons with Achilles tendinopathy

To evaluate the effects of overloading on Achilles tendons, differences in tendon mechanical properties between patients with Achilles tendinopathy and healthy subjects were assessed using ultrasonography and/or MRI. The results of various studies on this subject are displayed in Table 4.2.

Study	Exp. group	Contr. group	Findings
Leung and Griffith[19]	30 Achilles tendons; 21 patients (9 male 12 female)	100 Achilles tendons; 50 subjects 22 male 28 female	Tendinopathic tendons CSA > controls at midpoint and calcaneal insertion; disruption of fibrillar pattern in 20% of tendinopathic tendons vs. 0% controls; neovascularisation[a] in 46.7% of tendinopathic tendons vs. 0% in controls; focal calcification in 6.7% of tendinopathic tendons vs. 2% in controls
Child et al.[20]	16 male recreational runners with Achilles tendinopathy	16 male recreational runners	Achilles tendon thickness was greater in symptomatic Achilles tendon than controls, at site perpendicular to medial malleolus, but not at insertion. Achilles tendon strain at musculotendinous junction was larger in symptomatic Achilles tendon than in controls => higher compliance/lower stiffness
Arya and Kulig[21]	12 male runners with Achilles tendinopathy	12 male runners	Achilles tendon stiffness patients < controls; Achilles tendon elongation patients > controls; Achilles tendon CSA patients > controls; Achilles tendon stress patients < controls; Achilles tendon strain patients > controls; Young's modulus (stress/strain) patients < controls
Wang et al.[22]	17 male athletes with Achilles tendinopathy	Non-symptomatic leg of same subjects	Stiffness: lower in injured leg, hysteresis: higher in injured leg; elastic energy stored: lower in injured leg; elastic energy released: lower in injured leg

Table 4.2: Differences in tendon mechanical properties between patients with Achilles tendinopathy and healthy controls. [a]Influx of new blood vessels in the affected area.

All studies in Table 4.2 show that Achilles tendinopathy is associated with a larger CSA and a decrease in tendon stiffness. Since stiffness is directly related to the tendon CSA, it would be expected that a larger tendon CSA would yield a stiffer tendon. However, in the case of Achilles tendinopathy, the increase in CSA is most likely due to accumulation of fluid and disorganisation of collagen fibres.[21] So possible explanations for decreased stiffness in Achilles tendinopathy patients relate to disorganisation of tendon and collagen fibres, hypervascularisation (the random formation of blood vessels), degeneration of collagen fibres and an increase in extracellular matrix.[3] Disorganisation of the tendon fibres leads to an increased vulnerability for further (micro)trauma, which increases the risk for tendon rupture.[21]

Another factor that may contribute to the injury mechanism is a disturbed balance between energy storage and dissipation in the tendon: Wang et al.[22] found increased hysteresis in the injured Achilles tendon of patients with unilateral tendinopathy, indicative of increased dissipation of energy into heat. This causes an increase in metabolic demand and hyperthermia within the Achilles tendon, which may lead to tendon degeneration.

As indicated in the previous section injury, injury mechanisms of Achilles tendinopathy are best studied using longitudinal studies; all studies summarised in Table 4.2 have a cross-sectional study design. Therefore, their results reflect the pathological reaction of the tendon, but the mechanisms behind these reactions are still unknown.

Biomechanical risk factors for development of Achilles tendinopathy

Various risk factors for the development of Achilles tendinopathy can be found in the literature. Both intrinsic and running-related variables seem to contribute: in a prospective study, Mahieu et al.[23] found that people with low plantar flexor strength before the start of a running programme were more likely to develop Achilles tendinopathy. Using a similar design, Van Ginckel et al.[1] found a decrease in posterior–anterior displacement of the centre of force and a laterally directed force distribution underneath the forefoot at 'forefoot flat' in subjects who developed Achilles tendinopathy. This suggests that runners with a running pattern with less forward force transfer underneath the foot and a more lateral foot roll-over are more at risk of developing Achilles tendinopathy. Further, Almonroeder et al.[24] found in a cross-sectional study that non-rearfoot strike runners had greater Achilles tendon loading than rearfoot strike runners, suggesting that running style influences the loading on the tendon and thus may also influence the adaptation of the tendon.

The studies of Mahieu et al.[23], Van Ginckel et al.[1] and Almonroeder et al.[24] focus on the loading of the musculoskeletal structures. However, it is necessary to take into account the mechanical properties (i.e. tendon stiffness, CSA) of the Achilles tendon, as these reflect the loading capacity of the tendon. Such an analysis of loading and loading capacity would allow one to define individual loading threshold of the Achilles tendon.

CONCLUSION

In conclusion, the human Achilles tendon adapts to running by increasing its CSA. It is still unknown how long these adaptations take and which loading volume is required for the tendon tissues to adapt. One longitudinal study indicates that a 9-month running programme for novice runners does not lead to structural adaptations. Similarly, it is unknown which running volume and intensity will cause overloading of the tendons. When following a structured running programme, mechanical loading of the tendon is increased, which normally leads to tissue adaptations. If these adaptations do not occur, the runner is at risk for developing Achilles tendinopathy. Strength and plyometric training cause an increase in Achilles tendon CSA and stiffness. It is therefore advisable for endurance runners to add strength and/or plyometric exercises to their training programme in order to protect against Achilles tendon injury.

More research with a prospective design is needed to determine the relationship between running volume and tendon adaptation. Furthermore, adaptations in female subjects should be investigated, as there appears to be a gender difference in tendon adaptation. Also considering possible risk factors for the development of Achilles tendinopathy, prospective studies are needed.

REFERENCES

1 Van Ginckel A, Thijs Y, Hesar NG, Mahieu N, De Clercq D, Roosen P, Witvrouw E. Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: a prospective study. *Gait Posture* 2009; 29 (3): 387–391.

2 Knobloch K, Yoon U, Vogt PM. Acute and overuse injuries correlated to hours of training in master running athletes. *Foot Ankle Int.* 2008; 29 (7): 671–676.

3 Paavola M, Kannus P, Järvinen TA, Khan K, Józsa L, Järvinen M. Achilles tendinopathy. *J Bone Joint Surg Am.* 2002; 84 (11): 2062–2076.

4 Kjaer M, Magnusson P, Krogsgaard M, Boysen MøllerJ, Olesen J, Heinemeier K, et al. Extracellular matrix adaptation of tendon and skeletal muscle to exercise. *J Anat.* 2006; 208 (4): 445–450.

5 Buchanan CI, Marsh RL. Effects of exercise on the biomechanical, biochemical and structural properties of tendons. *Comp Biochem Physiol.* 2002; 133 (4): 1101–1107.

6 Magnusson SP, Langberg H, Kjaer M. The pathogenesis of tendinopathy: balancing theresponse to loading. *Nat Rev Rheumatol.* 2010; 6 (5): 262–268.

7 Kongsgaard M, Aagaard P, Kjaer M, Magnusson SP. Structural Achilles tendon properties in athletes subjected to different exercise modes and in Achilles tendon rupture patients. *J ApplPhysiol.* 2005; 99 (5): 1965–1971.

8 Kubo K, Tabata T, Ikebukuro T, Igarashi K, Yata H, Tsunoda N. Effects of mechanical properties of muscle and tendon on performance in long distance runners. *Eur J Appl Physiol.* 2010; 110 (3): 507–514.

9 Hansen P, Aagaard P, Kjaer M, Larsson B, Magnusson SP. Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. *J ApplPhysiol.* 2003; 95 (6): 2375–2380.

10 Abate M, Oliva F, Schiavone C, Salini V. Achilles tendinopathy in amateur runners: role of adiposity. *Muscles Ligaments Tendons J.* 2012; 2(1): 44–48.

11 Arampatzis A, Karamanidis K, Morey-Klapsing G, De Monte G, Stafilidis S. Mechanical properties of the triceps surae tendon and aponeurosis in relation to intensity of sport activity. *J Biomech.* 2007; 40 (9): 1946–1952.

12 Magnusson SP, Kjaer M. Region-specific differences in Achilles tendon cross-sectional area in runners and non-runners. *Eur J Appl Physiol.* 2003; 90 (5): 549–553.

13 Rosager S, Aagaard P, Dyhre-Poulsen P, Neergaard K, Kjaer M, Magnusson SP. Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scand J Med Sci Sports 2002*; 12 (2): 90–98.

14 Westh E, Kongsgaard M, Bojsen-Moller J, Aagaard P, Hansen M, Kjaer M, Magnusson SP. Effect of habitual exercise on the structural and mechanical properties of human tendon, in vivo, in men and women. *Scand J Med Sci Sports 2008*; 18 (1): 23–30.

15 Heinemeier K, Langberg H, Olesen JL, Kjaer M. Role of TGF-beta1 in relation to exercise-induced type I collagen synthesis in human tendinous tissue. *J ApplPhysiol.* 2003; 95 (6): 2390–2397.

16 Heinemeier KM, Kjaer M. In vivo investigation of tendon responses to mechanical loading. *J Musculoskelet Neuronal Interact.* 2011; 11(2): 115–123.

17 Fouré A, Cornu C, McNair PJ, Nordez A. Gender differences in both active and passive parts of the plantar flexors series elastic component stiffness and geometrical parameters of the muscle-tendon complex. *J Orthop Res.* 2012; 30 (5): 707–712.

18 Miller BF, Hansen M, Olesen JL, Flyvbjerg A, Schwarz P, Babraj JA, Smith K, Rennie MJ, Kjaer M. No effect of menstrual cycle on myofibrillar and connective tissue protein synthesis in contracting skeletal muscle. *Am J Physiol Endocrinol Metab.* 2005; 290 (1): E163–E168.

19 Leung JL, Griffith JF. Sonography of chronic Achilles tendinopathy: a case-control study. *J Clin Ultrasound* 2008; 36 (1): 27–32.

20 Child S, Bryant AL, Clark RA, Crossley KM. Mechanical properties of the Achilles tendon aponeurosis are altered in athletes with Achilles tendinopathy. *Am J Sports Med.* 2010; 38 (9): 1885–1893.

21 Arya S, Kulig K. Tendinopathy alters mechanical and material properties of the Achilles tendon. *J Appl Physiol.* 2010; 108 (3): 670–675.

22 Wang HK, Lin KH, Su SC, Shih TT, Huang YC. Effects of tendon viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in athletes. *Scand J Med Sci Sports* 2012; 22 (6): e147–e155.

23 Mahieu NN, Witvrouw E, Stevens V, Van Tiggelen D, Roget P. Intrinsic risk factors for the development of achilles tendon overuse injury: a prospective study. *Am J Sports Med.* 2006; 34 (2): 226–235.

24 Almonroeder T, Willson JD, Kernozek TW. The effect of foot strike pattern on Achilles tendon load during running. *Ann Biomed Eng.* 2013; 41 (8): 1758–1766.

CHAPTER 5: NO ADAPTATION IN ACHILLES TENDON STIFFNESS AFTER A 12-WEEK RUNNING PROGRAM FOR BEGINNERS

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ABSTRACT

The Achilles tendon is heavily loaded during running. In beginner runners, this leads to a high incidence of Achilles tendon injury. A stiffer Achilles tendon can withstand larger loads, which leads to lower tendon strains. However, little is known about the adaptation of Achilles tendon stiffness to running training. We studied changes in Achilles tendon stiffness before and after a 12-week running program for beginners. Second, we aimed to relate this change to Achilles tendon loading during running. Achilles tendon stiffness was measured in vivo, using ultrasonography, in 26 novice runners before and after following a 12-week running program and in 15 control subjects. Ankle plantar flexor moment during running was measured in the running group using a combination of motion capture and force platforms to estimate Achilles tendon loading during each step. Results showed no change in Achilles tendon stiffness after the running program. However, there was a medium, positive correlation between peak ankle moment during running and change in Achilles tendon stiffness ($R = 0.387$, $p = 0.034$), indicating that larger Achilles tendon loads during running lead to larger adaptations in Achilles tendon stiffness.

Key words: Achilles tendinopathy, biomechanics, novice runners

INTRODUCTION

Running programs for absolute beginners yield substantial increases in fitness level[1]. They are very popular amongst sedentary people who want to increase their physical activity, since they require minimal time and financial sacrifices. Besides stressing the cardiorespiratory system, the act of running causes mechanical loading on the tissues (bones, muscles and tendons) of the lower extremity. The Achilles tendon, responsible for transferring forces from three different calf muscles to the foot, is loaded with forces of up to 12.5 times body weight during each step[2]. During a typical running program for beginners, weekly training distance increases progressively, demanding tissue adaptations to withstand the increased loading.

Tendon stiffness reflects the ability of a tendon to resist change in length when pulled on by a given force[3]. Various studies showed that tendons adapt to increased loading by increasing stiffness. Both animal studies[4] and resistance training studies in humans[5–9] have found significant increases of Achilles tendon stiffness with training, and decreases following immobilization or detraining[9–11]. However, the effect of functional activities, such as walking and running, on Achilles tendon properties is less well established. In cross-sectional studies, elite[12] and recreational[13–15] runners had larger Achilles tendon CSA compared to non-runners, suggesting that Achilles tendon properties adapt to the loads induced by running. However, there is no evidence for a difference in Achilles tendon stiffness between runners and non-runners[8,15–18]. A longitudinal study by Hansen et al.[19] found no changes in Achilles tendon stiffness after 9 months of running training. However, athletes in sports that involve larger strains than endurance running, such as sprinters and ski jumpers, do develop larger Achilles tendon stiffness[16,20]. This suggests that the magnitude of strain is more important for increasing tendon stiffness than training volume. This finding is backed up by strength training studies that found larger increases in stiffness with high loads versus low loads[21].

Although tendons may show adaptations when put under mechanical stress, excessive strains and repetitive loading can cause Achilles tendon damage[22,23]. Chronic Achilles tendon injuries, often called Achilles tendinosis or Achilles tendinopathy, are certainly common in recreational runners. Studies showed that 8[24] to 10[25] percent of the participants in a three-month running program sustain an injury to the Achilles tendon. Although the mechanisms behind Achilles tendinopathy are poorly understood, it has been documented that, during the injury process, mechanical properties of the Achilles tendon are altered. Achilles tendinopathy has been associated with tendon fibre disruption and fluid accumulation[26] and, consequently, lower tendon stiffness[27–29] and larger cross-sectional area[27,28,30]. If Achilles tendon stiffness decreases while the force generating capacity of the attached muscles remains, there will be larger strains in the tendon[3], making a decrease in tendon stiffness an important risk factor for (further) injury. In addition, previous studies have shown that muscles adapt quicker to training than tendons[31], possibly causing a mismatch of muscle force generating capacity and tendon stiffness along the way. A relatively strong muscle attached to a relatively compliant tendon can lead to excessive tendon strains, which is a risk factor for tendon damage[3].

Since Achilles tendon loading is influenced by various factors including body weight, running speed and running style, adaptations may differ across individuals, depending on runner-specific Achilles tendon loading during running. Running style may influence the amount of tendon strain and therefore influence tendon adaptation to running. In runners with a forefoot strike pattern, where the ankle is more plantar flexed during ground contact and the forefoot makes ground contact first, peak Achilles tendon forces are higher compared to runners who land on their rearfoot.[32–34] Peak Achilles tendon forces will also be higher in heavier runners and in runners with a higher running speed. These individual differences in Achilles tendon loading per step may cause different tendon strains in different runners and therefore trigger adaptational responses in some, but not all runners. We therefore hypothesize that change in Achilles tendon stiffness is positively related to Achilles tendon loading, so that runners with higher Achilles tendon loads per step, will show larger increases in Achilles tendon stiffness after 12 weeks of training. Because Achilles tendon strain and Achilles tendon force are difficult to measure directly, we used ankle plantar flexor moment as an approximation of Achilles tendon force. According to the study of Lichtwark et al, ankle plantar flexion moment peaks around the same time as Achilles tendon strain[35]. Giddings et al. determined Achilles tendon force using finite element modelling and concluded that the shape of the Achilles tendon force curve corresponds qualitatively with the moment around the ankle joint.[36] Differences in foot strike pattern are also reflected in ankle plantar flexor moment, since a forefoot landing will cause a larger external moment arm and therefore a larger plantar flexor moment around the ankle joint.[37]

In order to get more insight in Achilles tendon injury mechanisms and to understand the influence of Achilles tendon stiffness on running performance, it is important to know how the tendon adapts to the increased mechanical loading imposed on the tendon during running. To our knowledge, no studies exist on the relationship between ankle moments and tendon adaptation during running in novice runners. Therefore, the aim of the present study is to determine changes in Achilles tendon stiffness after a 12-week running program for beginners and to relate these changes to the peak ankle plantar flexion moment during running. We hypothesized that changes in Achilles tendon stiffness are positively related to peak ankle moments during running.

METHODS

Sample size was calculated based on the findings of Albracht et al.[5] The training intervention in Albracht's study was of a similar duration (14 weeks) to our study, but consisted of a different exercise mode: resistance training. Since no running studies of similar duration to our study were available, Albracht's study was used for the power calculation. In the study of Albracht et al., Achilles tendon stiffness changed from 272 (SD: 48) to 315 (SD: 53) N/mm. Given an alpha level of 0.05 and a beta of 0.2, the required sample size was 11 subjects. Forty-four volunteers were recruited for participation in the running group of this study through social media, flyers, and advertisement in a local newspaper. Respondents were eligible for participation if they were between 18-60 years old, did not participate in any weight-bearing sports (involving running or jumping) for more than 1 hour per week in the year prior to the first measurement, and had no injuries in the three months prior to participation. In addition, 16 age-matched, inactive control subjects were recruited. Participants in the running group underwent a 3D running analysis as well as measurements of tendon stiffness. Control subjects only underwent the tendon measurements.

The training program consisted of 12 weeks of running training in which the training distance increased every week. Participants in the running group could choose between two programs: one that led from 1 to 30 minutes of continuous running and one that led from 10 to 45 minutes of continuous running. Twice a week, supervised training sessions were organized and participants were encouraged to perform a third session individually. Participants were instructed to run at a self-selected, comfortable pace and ran in their own running shoes. Participants recorded the number of sessions they attended and the training distance, as well as any pains and aches in a log book. In case of an injury, participants informed the researchers and were referred to a sports physician. Control group participants were instructed not to engage in any structural physical activity during the course of the study.

Participants visited the movement lab on two occasions: before and after the 12-week running program. First, participants in the running group underwent a 3D movement analysis to determine ankle moment during running. A 10-camera motion capture system (Vicon, Oxford, UK) recording at 150 Hz was used in combination with an extended Plug-In-Gait model with 48 reflective markers. Participants wore standardized, neutral running shoes (Asics Landreth 7). Participants warmed up on a treadmill after which they ran at a self-selected speed across the floor of the movement lab, in which a force platform (AMTI OR6-7, Watertown, USA) was embedded, capturing at 900 Hz. Ankle moments were calculated from three trials of the right leg and three trials of the left leg using Vicon Bodybuilder version 3.6.1.

Achilles tendon stiffness was measured in both the running and the control group using a combination of motion capture, a force transducer and ultrasonography, all synchronized in Vicon Nexus version 1.8.5. The method used for measuring Achilles tendon stiffness was adapted from the study of Kongsgaard et al.[38] Participants laid in prone position on an examination table. The ultrasound transducer (Telemed Echoblaster 128, Vilnius, Lithuania), capturing at 30 Hz, was fixed on the leg at the level of the musculotendinal junction (MTJ) using a custom-made cast. Eight reflective markers were placed on the lower leg and foot.

First, two trials were recorded in which the ankle was passively rotated by the researcher over the full range of motion. These measurements were later used to calculate the Achilles tendon moment arm using the tendon travel method[39] and to determine the movement of the MTJ due to passive rotation of the ankle. Second, the subjects performed isometric ramp maximal voluntary contractions (MVC's). In order to measure the Achilles tendon force (F_{AT}), a foot plate was attached to the plantar surface of the foot. A cable, which was attached to a force transducer (HBM

U2A, Darmstadt, Germany), was then attached to the foot plate (Figure 5.1). Three reflective markers were attached to the cable.

Participants were instructed to build up the isometric plantar flexion force over three seconds to maximum effort, and then to release the force over three seconds to full relaxation. Three ramp MVC's were recorded of each leg, with one minute of rest in between.

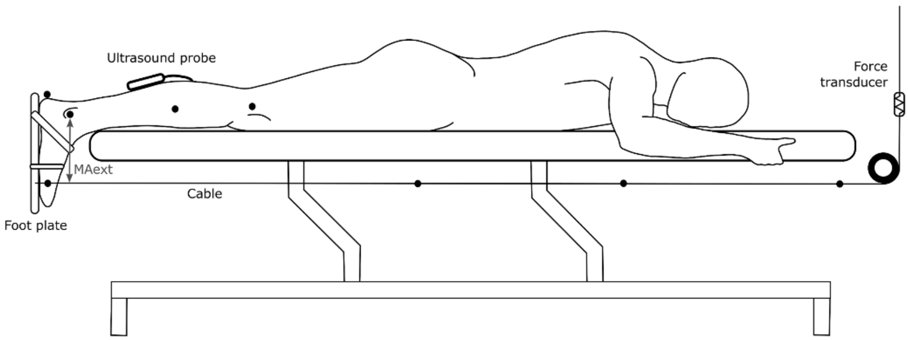

Figure 5.1: Setup for the Achilles tendon stiffness measurements.

For each leg of every subject, the MVC trial with the highest peak force, good ultrasound image quality (aponeurosis and muscle fibres clearly visible, indicating that the ultrasound probe was positioned in the right plane), and good marker visibility was selected for further processing. Marker trajectories and the force transducer signal were filtered using a 4^{th} order Butterworth filter with a cut-off frequency of 10 Hz. The MTJ position during the passive and ramp MVC trials was tracked manually by indicating the position of the MTJ on the ultrasound image in Matlab. Change in MTJ position (ΔMTJ) was then calculated from the MTJ coordinates. The internal moment arm of the Achilles tendon was calculated over an interval of 15 degrees ankle rotation (7.5 degrees of plantar- and dorsiflexion from the neutral position) by dividing the dL in mm by the change in ankle angle in radians during the passive ankle rotation[40]:

$$\mathrm{MA_{int}} = \frac{\Delta \mathrm{MTJ}}{\Delta \mathrm{ankle\ angle}}$$

Also, the ΔMTJ per degree of passive rotation (angle correction factor) was calculated to later correct the dL for ankle rotation occurring during the ramp MVC's.

Achilles tendon stiffness was calculated based on the ramp MVC trial data. Change in Achilles tendon length (ΔL) was calculated as ΔMTJ during an isometric contraction. ΔL was corrected for change in ankle angle, which occurs even during 'isometric' contractions. This was done by adding the change in ankle angle multiplied by the angle correction factor from the passive trials. Achilles tendon stiffness was defined as the slope of the F_{AT} – Achilles tendon length relationship from 50-100% of maximal F_{AT}:

$$F_{AT} = \frac{F_{cable} * MA_{ext}}{MA_{int}}$$

$$\text{Achilles tendon stiffness} = \frac{\Delta L}{\Delta F_{AT}}$$

Differences in Achilles tendon stiffness between the pre- and the posttest were analysed using a one-way repeated measures ANOVA. Associations between loading parameters (peak ankle moment during running) and change in Achilles tendon stiffness and maximal isometric ankle plantar flexion moment were calculated using Pearson correlation coefficients. Pearson correlations were interpreted using Cohen's classification.[41]

RESULTS

Twenty six of the forty four participants in the running group finished the running program successfully, completing on average 29 (SD: 5) running sessions, which makes an average of 2.4 sessions per week. Of the 18 participants who did not finish the program, three participants dropped out due to a running-related injury (one person had lower leg pain, two had knee pain). The remaining 15 drop-outs were due to illness, non-running related injury, lack of time or lack of motivation. None of the participants developed an Achilles tendon injury. Due to technical problems, tendon stiffness data of 4 subjects and ankle moment during running of 2 subjects had to be removed, leaving 22 subjects (8 men, 14 women) for statistical analysis. Subject characteristics are displayed in Table 5.1.

	N	Age (years)	Height (cm)	Weight (kg)
Experimental	22 (8 m, 14f)	30 (SD: 12)	173 (SD: 10)	70 (SD: 12)
Control	16 (8 m, 8 f)	26 (SD: 11)	172 (SD: 8)	63 (SD: 8) *

*Table 5.1: Characteristics of the analysed subjects. *: difference between experimental and control group; p < 0.05*

There was no interaction effect between group and training for Achilles tendon stiffness or isometric ankle moment. There were no significant differences in Achilles tendon stiffness between the pretest and the posttest (Figure 5.2, Table 5.2). However, there was a significant increase in peak isometric ankle plantar flexion moment during the MVC's in both groups, indicating that participants from both the running and the control group increased their isometric plantar flexion strength. Peak ankle flexor moment during running did not change after training. Within the running group, there were no interaction effects of sex * training or running program * training, indicating that there were no differences in the responses to running training between sexes or between people who followed the beginner training program and people who followed the intermediate training program.

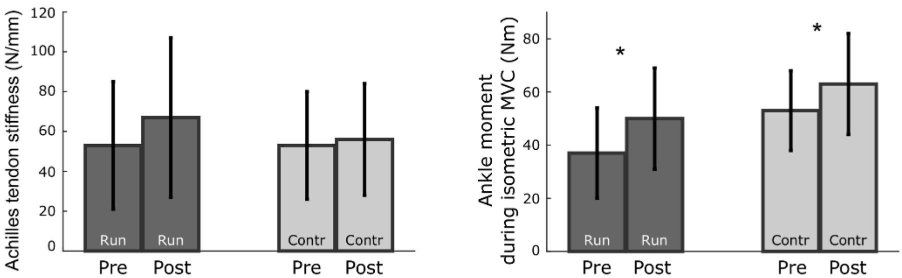

*Figure 5.2: Achilles tendon stiffness (left panel) and isometric ankle plantar flexion moment (right panel) at baseline and after 12 weeks in novice runners (dark grey) and controls (light grey). *: difference between pre- and posttest; p < 0.05*

Variable	Pretest runners	Posttest runners	p	Pretest controls	Posttest controls	p
Achilles tendon stiffness (N/mm)	53 (SD: 32)	67 (SD: 40)	0.080	53 (SD: 27)	56 (SD: 28)	0.568
Ankle plantar flexor moment during MVC (Nm)	37 (SD: 17)	50 (SD: 19)	<0.001	53 (SD: 15)	63 (SD: 19)	0.003

Table 5.2: Achilles tendon stiffness and ankle plantar flexor moment during an isometric ramp MVC before and after 12 weeks of training (running group) and no intervention (control group).

In the running group, a significant, medium correlation coefficient (R = 0.387, p = 0.034) was found between peak ankle plantarflexion moment during running and change in Achilles tendon stiffness, indicating that in people with higher Achilles tendon loads during running, Achilles tendon stiffness increased slightly more than in participants with lower Achilles tendon loads. Isometric ankle plantar flexor moment was related to Achilles tendon stiffness (R = 0.396, p = 0.001, measured in both groups).

DISCUSSION

The aim of the present study was to determine changes in Achilles tendon stiffness after a 12-week running program in a population of novice runners. A second aim was to relate ankle plantar flexor moments during running to adaptations in Achilles tendon stiffness. It was hypothesized that participants who displayed larger ankle plantar flexor moments, causing larger tendon strain, would show larger increases in Achilles tendon stiffness.

The results from this study indicate that there are no significant changes in Achilles tendon stiffness after the 12-week running program. The absence of change in Achilles tendon stiffness is in concordance with the study of Hansen[19], who also did not find a change in Achilles tendon stiffness with running training in a population of novice runners. Against expectations, ankle plantar flexion moment increased in the control group as well as in the running group. Although this increase in plantar flexor strength was smaller in the control group than in the running group (15% and 35%, respectively), there was no significant interaction effect between training and group. The change in plantar flexor strength can therefore not be attributed to the running training. Since we did not monitor the physical activity of the control group, we cannot rule out a training effect due to increased activity of the control group. The increase in ankle plantar flexor strength may also be due to a learning effect or increased motivation during the posttest.

A significant, medium sized correlation was found between peak ankle plantar flexion moment during running and change in Achilles tendon stiffness. This confirmed our hypothesis that runners with higher peak ankle plantar flexion moments during running increased their tendon stiffness more compared to runners with lower peak ankle plantar flexion moments. To our knowledge, this is the first longitudinal study to report on the relationship between ankle plantar flexion moments during running and tendon stiffness adaptation. A cross-sectional study from Kubo et al.[42] did not find a relationship between foot strike pattern, which is related to ankle plantar flexion moment, and Achilles tendon stiffness. However, the population from that study (highly trained endurance runners) is very different from the population in our study, which may explain the different findings. Possibly, the large total training volume accumulated over years of training washes out the effect of ankle moment during running.

When comparing the values from our study to previous studies, it is obvious that both the stiffness and the isometric ankle moments in the current study are lower than reported in some of the literature, even for untrained subjects. However, it must be noted that Achilles tendon stiffness varies greatly between studies, and our values are within the range of what was previously found[8,19]. The low isometric ankle moments that we have measured may be partially due to the measurement setup, which was different from the commonly used isokinetic dynamometer for ankle torque measurement. Our setup has the advantage that the subject’s knees are fully extended in the prone position, making additional torque from knee extension impossible. The disadvantage is however, that this setup may allow for slightly more plantar flexion during the ‘isometric’ contraction than a setup using a dynamometer. This increased plantar flexion angle may lead the gastrocnemius and soleus length away from the optimal length reducing the maximal force capacity of the muscles. Most importantly, since we analysed the change in tendon stiffness within subjects, this issue will not affect our conclusions.

Despite the limited sample size, we can concluded that 12 weeks of running training is too short to yield adaptations in Achilles tendon mechanical properties. Kjaer et al.[43] have already established that tendons take longer to adapt to increased mechanical loads than muscles. However, it remains questionable whether tendon stiffness changes with running training at all, since Hansen et al.[19] did not find a change in Achilles tendon stiffness even after nine months of running training.

A few limitations to the study design have been identified. First, the large standard deviations for the Achilles tendon stiffness measurements lead to questions regarding the reproducibility of the Achilles tendon stiffness measurement. The measurement method was adapted from the study of Kongsgaard et al.[38], who found good reproducibility (between-day correlation coefficient of 0.84) of the Achilles tendon stiffness measurements between two different test days. However, we positioned the subjects differently (prone versus seated position) than in the study of Kongsgaard et al. and used a different ultrasound machine and custom software for MTJ position tracking. These factors may influence reproducibility. Second, because of the relatively small range in peak plantar flexor moments during running, the present study could have benefitted from a larger sample size with a larger variety in running styles (for example, forefoot strikers and rearfoot strikers). Training studies in novice runners often suffer from high drop-out rates, and the present study is no exception. Finally, the control group was not entirely matched to the experimental group: the control subjects were, on average, four years younger and seven kg (10%) lighter compared to the participants in the experimental group. Although there is evidence that Achilles tendon stiffness decreases with age[44], there was no difference in Achilles tendon stiffness at baseline in our sample, indicating that a difference of, on average, four years does not influence Achilles tendon stiffness. The higher average body weight of the experimental group may have influenced the Achilles tendon loading during locomotion: Achilles tendon loading during running depends, among other factors, on body weight.[2] Therefore, the control group may have experienced lower Achilles tendon loads during activities such as walking compared to the experimental group. Inter-individual differences in Achilles tendon loading during locomotion was the motivation for the second aim of our study: to associate Achilles tendon loading during running with changes in Achilles tendon stiffness after a 12-week training program. The results of this part of the study were calculated only on data from the running group and will therefore not be influenced by the difference in body weight between the groups. Further studies on Achilles tendon adaptations in novice runners should therefore aim at recruiting a higher number of subjects and following them for a longer period of time.

CONCLUSION

In conclusion, Achilles tendon stiffness did not change in a group of novice runners following a 12-week running program. Change in Achilles tendon stiffness was correlated to peak ankle plantar flexion moment during running, indicating that Achilles tendon stiffness increases more in runners with a running style that imposes larger strains on the Achilles tendon.

REFERENCES

1 Scharhag-Rosenberger F, Meyer T, Walitzek S, et al. Time course of changes in endurance capacity: A 1-yr training study. *Med Sci Sports Exerc* 2009; 41(5):1130–1137.

2 Komi P V., Fukashiro S, Jarvinen M. Biomechanical loading of Achilles tendon during normal locomotion. *Clin Sports Med* 1992; 11(3):521–531.

3 Pearson SJ, McMahon J. Lower limb mechanical properties: determining factors and implications for performance. *Sport Med* 2012; 42(11):929–940.

4 Buchanan CI, Marsh RL. Effects of exercise on the biomechanical, biochemical and structural properties of tendons. *Comp Biochem Physiol Part A* 2002; 133:1101–1107.

5 Albracht K, Arampatzis A. Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. *Eur J Appl Physiol* 2013; 113(6):1605–1615.

6 Kubo K, Kanehisa H, Fukunaga T. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol* 2002; 538(1):219–226.

7 Kubo K, Morimoto M, Komuro T, et al. Effects of plyometric and weight training on muscle-tendon complex and jump performance. *Med Sci Sports Exerc* 2007; 39(10):1801–1810.

8 Kubo K, Ikebukuro T, Yata H, et al. Effects of training on muscle and tendon in knee extensors and plantar flexors in vivo. *J Appl Biomech* 2010; 26:316–323.

9 Kubo K, Ikebukuro T, Maki A, et al. Time course of changes in the human Achilles tendon properties and metabolism during training and detraining in vivo. *Eur J Appl Physiol* 2012; 112:2679–2691.

10 Kinugasa R, Hodgson J a, Edgerton VR, et al. Reduction in tendon elasticity from unloading is unrelated to its hypertrophy. *J Appl Physiol* 2010; 109:870–877.

11 Reeves ND, Maganaris CN, Ferretti G, et al. Influence of 90-day simulated microgravity on human tendon mechanical properties and the effect of resistive countermeasures. *J Appl Physiol* 2005; 98:2278–2286.

12 Kongsgaard M, Aagaard P, Kjaer M, et al. Structural Achilles tendon properties in athletes subjected to different exercise modes and in Achilles tendon rupture patients. *J Appl Physiol* 2005; 99:1965–7191.

13 Abate M, Oliva F, Schiavone C, et al. Achilles tendinopathy in amateur runners: role of adiposity (Tendinopathies and obesity). *Muscles Ligaments Tendons J* 2012; 2(1):44–48.

14 Magnusson SP, Beyer N, Abrahamsen H, et al. Increased cross-sectional area and reduced tensile stress of the Achilles tendon in elderly compared with young women. *Journals Gerontol Ser A* 2003; 58A(2):123–127.

15 Rosager S, Aagaard P, Dyhre-Poulsen P, et al. Load-displacement properties of the human triceps surae aponeurosis and tendon in runners and non-runners. *Scand J Med Sci Sports* 2002; 12:90–98.

16 Stafilidis S, Arampatzis A. Muscle - tendon unit mechanical and morphological properties and sprint performance. *J Sports Sci* 2007; 25(9):1035–1046.

17 Karamanidis K, Arampatzis A. Mechanical and morphological properties of different muscle-tendon units in the lower extremity and running mechanics: effect of aging and physical activity. *J Exp Biol* 2005; 208:3907–3923.

18 Westh E, Kongsgaard M, Bojsen-Moller J, et al. Effect of habitual exercise on the structural and mechanical properties of human tendon, in vivo, in men and women. *Scand J Med Sci Sports* 2008; 18:23–30.

19 Hansen P, Aagaard P, Kjaer M, et al. Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. *J Appl Physiol* 2003; 95:2375–2380.

20 Wiesinger HP, Rieder F, Kösters A, et al. Are Sport-Specific Profiles of Tendon Stiffness and Cross-Sectional Area Determined by Structural or Functional Integrity? *PLoS One* 2016; 11(6):1–16.

21 Arampatzis A, Karamanidis K, Albracht K. Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude. *J Exp Biol* 2007; 210:2743–2753.

22 Wren T a. L, Lindsey DP, Beaupré GS, et al. Effects of Creep and Cyclic Loading on the Mechanical Properties and Failure of Human Achilles Tendons. *Ann Biomed Eng* 2003; 31:710–717.

23 Andarawis-Puri N, Flatow EL. Tendon fatigue in response to mechanical loading. *J Musculoskelet Neuronal Interact* 2011; 11(2):106–114.

24 Van Ginckel A, Thijs Y, Hesar NGZ, et al. Intrinsic gait-related risk factors for Achilles tendinopathy in novice runners: a prospective study. *Gait Posture* 2009; 29:387–391.

25 Taunton JE, Ryan MB, Clement DB, et al. A prospective study of running injuries: the Vancouver Sun Run “In Training” clinics. *Br J Sports Med* 2003; 37:239–244.

26 Aström M, Gentz CF, Nilsson P, et al. Imaging in chronic Achilles tendinopathy: a comparison of ultrasonography, magnetic resonance imaging and surgical findings in 27 histologically verified cases. *Skeletal Radiol* 1996; 25(7):615–620.

27 Arya S, Kulig K. Tendinopathy alters mechanical and material properties of the Achilles tendon. *J Appl Physiol* 2010; 108:670–675.

28 Chimenti RL, Flemister AS, Tome J, et al. Altered tendon characteristics and mechanical properties associated with insertional achilles tendinopathy. *J Orthop Sports Phys Ther* 2014; 44(9):680–689.

29 Wang H-K, Lin K-H, Su S-C, et al. Effects of tendon viscoelasticity in Achilles tendinosis on explosive performance and clinical severity in athletes. *Scand J Med Sci Sports* 2012; 22:e147–e155.

30 Leung JLY, Griffith JF. Sonography of Chronic Achilles Tendinopathy: a case-control study. *J Clin Ultrasound* 2008; 36(1):27–32.

31 Kubo K, Ikebukuro T, Yata H, et al. Time course of changes in muscle and tendon properties during strength training and detraining. *J Strength Cond Res* 2010; 24(2):322–331.

32 Komi P V. Relevance of in vivo force measurements to human biomechanics. *J Biomech* 1990; 23(Suppl. 1):23–34.

33 Kulmala J-P, Pasanen K, Parkkari J. Forefoot strikers exhibit lower running-induced knee loading than rearfoot strikers. *Med Sci Sport Exerc* 2013; 45(12):2306–2313.

34 Almonroeder T, Willson JD, Kernozek TW. The effect of foot strike pattern on achilles tendon load during running. *Ann Biomed Eng* 2013; 41(8):1758–1766.

35 Lichtwark GA, Bougoulias K, Wilson AM. Muscle fascicle and series elastic element length changes along the length of the human gastrocnemius during walking and running. *J Biomech* 2007; 40:157–164.

36 Giddings VL, Beaupré GS, Whalen RT, et al. Calcaneal loading during walking and running. *Med Sci Sport Exerc* 2000; 32(3):627–634.

37 Lyght M, Nockerts M, Kernozek TW, et al. Effects of Foot Strike and Step Frequency on Achilles Tendon Stress During Running. *J Appl Biomech* 2016; 32:365–372.

38 Kongsgaard M, Nielsen CH, Hegnsvad S, et al. Mechanical properties of the human Achilles tendon, in vivo. *Clin Biomech* 2011; 26:772–777.

39 Maganaris CN, Baltzopoulos V, Sargeant a J. In vivo measurement-based estimations of the human Achilles tendon moment arm. *Eur J Appl Physiol* 2000; 83:363–369.

40 Fath F, Blazevich AJ, Waugh CM, et al. Direct comparison of in vivo Achilles tendon moment arms obtained from ultrasound and MR scans. *J Appl Physiol* 2010; 109:1644–1652.

41 Cohen J. *Statistical power analysis for the behavioral sciences*. 2nd ed. Hillsdale,NJ, Erlbaum, 1988.

42 Kubo K, Miyazaki D, Tanaka S, et al. Relationship between Achilles tendon properties and foot strike patterns in long-distance runners. *J Sports Sci* 2015; 33(7):665–669.

43 Kjaer M, Langberg H, Heinemeier K, et al. From mechanical loading to collagen synthesis, structural changes and function in human tendon. *Scand J Med Sci Sports* 2009; 19:500–510.

44 Csapo R, Malis V, Hodgson J, et al. Age-related greater Achilles tendon compliance is not associated with larger plantar flexor muscle fascicle strains in senior women. *J Appl Physiol* 2014; 116:961–969.

CHAPTER 6: NOVICE RUNNERS SHOW GREATER CHANGES IN KINEMATICS WITH FATIGUE COMPARED WITH COMPETITIVE RUNNERS

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ABSTRACT

Fatigue, developed over the course of a run, may cause changes in running kinematics. Training status may influence the effect of fatigue on running kinematics, since well trained, competitive runners are used to running until exhaustion, whereas novice runners are not. This study aimed to determine changes in running kinematics during an exhaustive run in both novice (NOVICE) and competitive (COMP) long distance runners. 15 NOVICE and 15 COMP runners performed a treadmill run until voluntary exhaustion at 3200 m time trial pace. Joint angles and global trunk and pelvis angles were recorded at the beginning and at the end of the run. In both groups, peak pelvic anterior tilt, pelvic rotation range of motion (both during stance phase) and ankle plantar flexion during swing phase increased after the exhaustive run. There was a significant interaction effect between group and exhaustion for peak forward trunk lean, which increased only in the NOVICE group, and for hip abduction during mid-swing, which increased in NOVICE and decreased in COMP runners. In conclusion, NOVICE runners showed larger kinematic adjustments when exhausted than COMP runners. This may affect their running performance and should be taken into account when assessing a runner's injury risk.

Keywords: running; performance; biomechanics; training.

INTRODUCTION

Running is a convenient and time-efficient way of becoming and staying physically active, which has led to an increase in the popularity of running since the 1970s. Unfortunately, running is also associated with a high injury risk with yearly incidence estimates ranging from 20 to 70%[1]. The vast majority of running injuries can be attributed to overuse injuries resulting from the accumulated repetitive loads placed upon the lower limb musculoskeletal tissues. Injury risk is associated with high weekly training distance[2] as well as lack of running experience[3], putting both competitive long-distance runners and novice runners at risk of developing overuse injuries.

The development of overuse injuries has been associated with kinematic variables of all lower limb joints: increased hip internal rotation[4,5], increased hip adduction[5,6], increased knee internal rotation[5,6] and increased ankle pronation[7]. Some of these variables, such as increased ankle pronation[8] and increased knee internal rotation[9,10], as well as increased rearfoot eversion[5,8,11], which is a component of ankle pronation, have been reported to occur with the development of fatigue over the course of a run.

Since ankle pronation, rearfoot eversion and knee internal rotation are all variables that have been associated with the development of overuse injuries, the risk of developing overuse injuries may be magnified during running in a fatigued state. Changes in running kinematics with fatigue may be more prominent in novice runners, since they lack the training status and technical skills to maintain their non-fatigued kinematics towards the end of an exhaustive run.

Most studies on kinematic changes with running fatigue focused on recreational runners[8,9,12–14] or runners with a particular overuse injury[10,15], while studies including well trained, competitive runners are less common. Competitive long-distance runners may be more resistant to changes with fatigue compared with novice runners due to their better training status. To date, the three studies investigating fatigue effects on running kinematics have examined competitive runners only[11,16,17]. Abt et al.[16] found no changes in kinematics whereas Clansey et al.[11] found increased peak rearfoot eversion with fatigue. Strohrmann et al. [17] uniquely included runners of various skill levels. Their group of highly trained runners however, included only three participants. They found increased trunk forward lean and decreased heel lift with exhaustion across all participants, with more pronounced changes in beginner runners.

All of the above studies restricted the statistical analysis to discrete data (i.e. peak joint angles). This approach discards a significant amount of phase data and importantly results in the loss of critical temporal (timing) events. Furthermore, while most studies compute peak joint angles during the stance phase of running, the swing phase is often neglected. Statistical parametric mapping (SPM) analyses differences in whole curves rather than peak values[18], allowing for the comparison of joint angles within and between groups across the entire stride cycle. Therefore, the purpose of the present study was to identify changes in the peak joint angles during stance as well as the kinematic waveforms of a whole stride cycle after an exhaustive run in novice as well as competitive long-distance runners. Second, we aimed to determine whether novice runners and competitive runners respond differently to an exhaustive run. It was hypothesised that competitive runners, due to their better training status, would display less pronounced changes in kinematics compared with novice runners. More specific, ankle eversion and trunk forward lean were expected to increase more in novice runners compared with well trained, competitive runners.

METHODS

Adequate sample size was calculated based on the results of Derrick et al.[12], who used a similar exhaustive protocol. Based on their findings (peak knee angle 127.7 ± 1.4° pre-exhaustion and 123.8 ± 1.5 post-exhaustion; peak rearfoot angle -6.5 ± 1.4 pre-exhaustion and -7.8 ± 1.4 post-exhaustion) a sample size of 12 participants per group with an effect size of 0.93 and a power of 0.9 was calculated. To account for possible data loss, 15 novice runners and 15 competitive long-distance runners volunteered to participate in the study. Novice runners (NOVICE) were included if their weekly running distance was less than 10 km/week and if they did not have a history of competitive running, or following a running training program. Yet, they had to be able to finish a 3200 m time trial without pausing or walking. Participants were included in the competitive (COMP) group if they were participating in running competitions, had at least 3 years of running experience and an average weekly training distance of 70 km/week for the male athletes and 50 km/week for the female athletes. Exclusion criteria for both groups were: pulmonary, neurological or cardiovascular diseases, obesity (BMI>30), use of orthopaedic devices (except custom orthotics) and musculoskeletal injuries to the lower limb or back in the 6 months prior to participation in the study. Written informed consent was obtained from the participants prior to participation in the study in accordance with the declaration of Helsinki. The study was approved by the local ethics committee (Commissie Medische Ethiek KU Leuven) under number S55656.

The study protocol consisted of two testing sessions, which were performed one week apart, in concordance with the protocol followed by Derrick et al.[12] During the first session, participants ran a 3200 m time trial on an outdoor 400 m running track at maximal effort. Time was recorded to calculate average running speed. To assess exhaustion level, BORG score[19] at completion of the time trial was recorded. The test was considered successful if a BORG score of at least 17/20 was achieved.

In the second session, a three dimensional kinematic running analysis was performed using a 10 camera VICON motion capture system (Vicon, Oxford, UK) capturing at 150 Hz. Forty-two reflective markers were placed on anatomical landmarks on the trunk and lower limb of the participants (Figure 6.1). Cluster markers were used on the thighs and shanks.

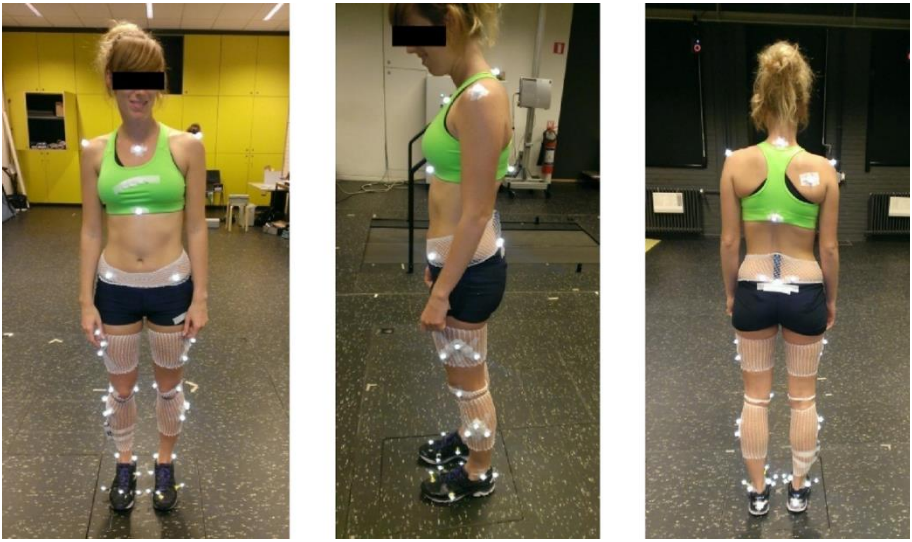


Figure 6.1: marker placement.

Foot markers protruded through holes in the shoe in order to capture accurate foot motion. Before the running trials, a standing calibration trial was recorded in which the participant was standing upright with the hips, knees and ankles in neutral positions. During the dynamic measurements, participants ran on a force-instrumented treadmill (Forcelink, Culemborg, the Netherlands), sampling at 1000 Hz. Participants wore standardised, neutral running shoes (Asics Gel Landreth 7, Japan) provided by the researchers and were allowed to use their own custom orthotics. Markers were not removed during the entire protocol.

Before starting the exhaustive run, a static calibration trial was captured and baseline heart rate and BORG score were recorded. Participants were allowed to walk and then jog at 1.94 m/s for two minutes each to familiarise themselves with the treadmill. Although it is possible to walk at a 1.94 m/s pace, participants were instructed to run. Hereafter, the protocol was slightly different for the two groups due to the speed limitation of the instrumented treadmill (Figure 6.2). For the COMP runners, two trials at the maximum speed of the instrumented treadmill (3.33 m/s) were recorded. Then, the COMP runners ran at their average running speed (AvS) from the 3200 m time trial on a different (non-instrumented) treadmill, until voluntary exhaustion. When the COMP participants indicated that they were exhausted, they were instructed to run back to the instrumented treadmill, where two trials at 3.33 m/s were recorded. Both treadmills were located in adjacent rooms and there was minimal time between the exhaustive run and the start of the measurement (approximately 30 seconds). NOVICE runners ran at their AvS until voluntary exhaustion. Two 10-second trials at AvS were recorded in the second minute of the exhaustive run. When the participants indicated that they were exhausted, two more trials at AvS were recorded. For both groups, BORG score and heart rate at the end of the test were recorded. The test was considered successful if a BORG score of at least 17/20 was reached.

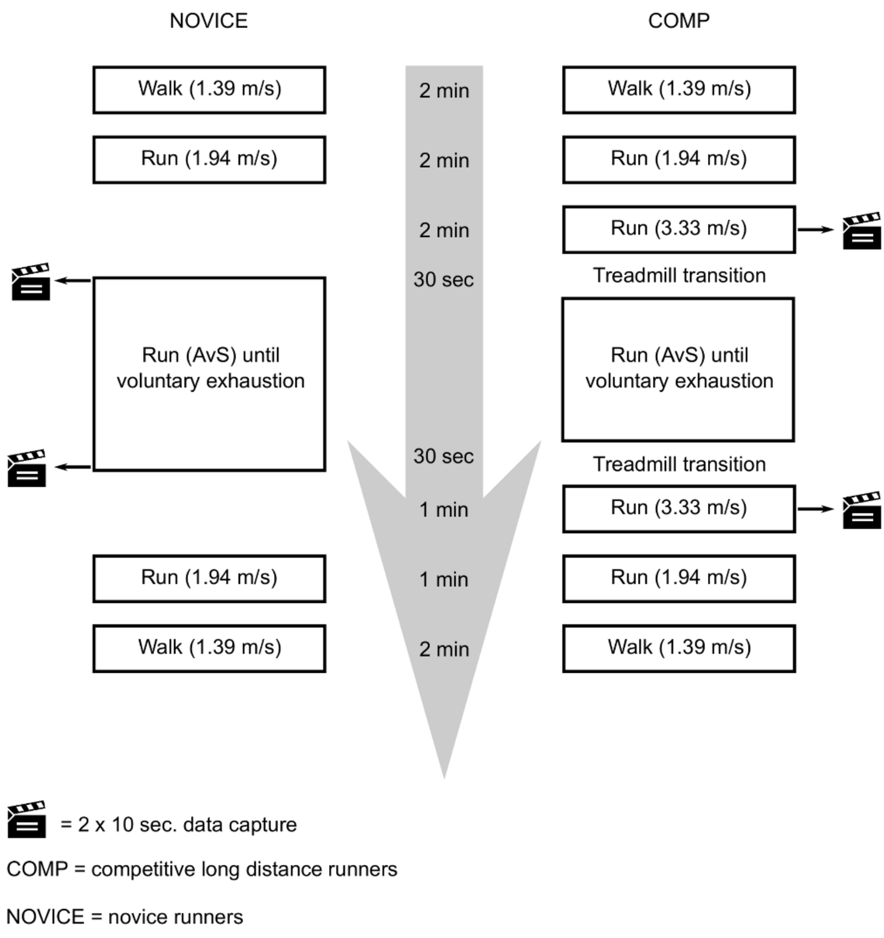


Figure 6.2: measurement protocol.

Two 10-second trials were selected from each running interval (AvS for the NOVICE runners, and 3.33 m/s for the COMP runners), both at the beginning and the end of the exhaustive run based on the quality of the marker data. Marker trajectories were filtered using a fourth-order low-pass Butterworth filter with a cut-off frequency of 15 Hz. Joint kinematics were calculated using Vicon Body Builder 3.6.1 software (Vicon, Oxford, UK). Joint angles were referenced to the proximal segment. Knee joint centre was located in the middle of the medial and lateral epicondyles. The ankle joint centre was located in the middle of the medial and lateral malleoli. Hip joint centre was calculated based on the pelvis depth, width and leg length according to the model of Davis[20]. Global trunk and pelvis angles were calculated, defined as the angle of the segment relative to the lab coordinate system. Vertical oscillation of the centre of mass was estimated by computing the mean vertical amplitude of the marker on the sacrum during the running trial.

Vertical ground reaction forces from the force plate in the treadmill were used to detect foot strike and toe off. Ground reaction force signals were filtered using a fourth-order, low-pass Butterworth filter with a cut-off frequency of 15 Hz. Ground contact was defined as the intervals were the vertical ground reaction force signal exceeded a threshold of 30 N. Stride time was calculated as the time between two foot strikes of the same foot and stance time was calculated as time between foot strike and toe-off. Joint angles were then calculated for each stride, averaged over the two 10-second trials and normalised to percentage of gait cycle, creating a mean for each joint angle in each leg (hip, knee and ankle) or individual (trunk and pelvis). For each participant, both the left and right leg were analysed, resulting in 30 trunks and 60 legs for statistical analysis.

All variables were checked for normality using a Shapiro-Wilk test. Differences in changes of peak angles within groups during stance phase were analysed using a repeated measures ANOVA for the normally distributed variables, and with a Wilcoxon signed rank test for the not normally distributed variables. To investigate if these changes are different between groups, a two-way ANOVA was used to calculate interaction effects between group and exhaustion. In addition, the waveforms of the hip, knee, angle joint angles and global trunk and pelvis angles were analysed using one-dimensional SPM. This method allows for evaluating changes in joint angles with exhaustion across the whole stride cycle. The effect of exhaustion on joint angles within groups was analysed using a SPM two-tailed repeated measures t-test. The SPM t-test yielded a t-curve, or SPM(t), of which the significance was determined using random field theory. The group × exhaustion interaction effect was used as a measure of different adaptation strategies to exhaustion between groups. This was analysed using a SPM two-way ANOVA with repeated measures on one factor (exhaustion)[21]. Open source code for conducting SPM tests was obtained from http://www.spm1d.org and implemented in Matlab version R2014a. Group mean joint angles were computed for each time point along the stride cycle. Alpha level was set at 0.05.

RESULTS

The COMP group (5 females, 10 males) and the NOVICE group (6 females, 9 males) were similar in age (COMP: 22 ± 4 years; NOVICE: 21.1 ± 1 years), height (COMP: 179 ± 8 cm; NOVICE: 177 ± 8 cm), and weight (COMP: 64 ± 6 kg; NOVICE: 69 ± 6 kg). COMP runners ran on average 77 ± 17 km/week and had been running for 10 ± 3 years. AvS was 2.75 ± 0.50 m/s for the NOVICE runners and 4.88 ± 0.57 m/s for the COMP runners. Mean time to exhaustion was 1693 ± 588 s for the NOVICE runners and 947 ± 284 s for the COMP runners.

When analysing the changes in peak joint angles during stance phase (Table 6.1), in the NOVICE group, increases in peak trunk flexion (3.0°, $p < 0.05$), trunk rotation ROM (3.5°, $p < 0.05$), peak pelvic anterior tilt (2.0°, $p < 0.05$), pelvic rotation ROM (2.4°, $p < 0.05$), peak hip flexion (0.9°, $p < 0.05$), peak knee extension (1.8°, $p < 0.05$), and a decrease in peak ankle abduction (3.6°, $p < 0.05$) were found. The increase in peak flexion may be a result of the increased pelvic anterior tilt, since these are interdependent due to the definition of the hip axis definition. In the COMP group, an increase in pelvic anterior tilt (0.9°, $p < 0.01$), pelvic obliquity ROM (1.6°, $p < 0.05$) and pelvic rotation ROM (2.3°, $p < 0.01$), a decrease in peak hip adduction (1.3°, $p < 0.01$), an increase in peak knee abduction (2.3°, $p < 0.01$) and a decrease in ankle plantar flexion (3.1°, $p < 0.05$) were found.

	Angle	**Mean difference novice runners (degrees ± SD)**	**p-value fatigue effect novice runners**	**Mean difference Competitive runners (degrees ±SD)**	**p-value fatigue effect competitive runners**	**p-value interac-tion effect**
Trunk	Flexion	3.0 ± 4.2	$0.021^{b,*}$	0.2 ± 1.9	0.759^{a}	0.037*
	Latero flexion ROM	1.8 ± 4.5	0.075^{b}	0.5 ± 1.8	0.335^{a}	0.312
	Rotation ROM	3.5 ± 4.7	$0.034^{a,*}$	3.2 ± 7.2	0.116^{a}	0.930
Pelvis	Anterior tilt	2.0 ± 2.1	$0.010^{a,*}$	0.9 ± 0.6	$<0.001^{a,*}$	0.195
	Obliquity ROM	1.1 ± 2.5	0.172^{a}	1.6 ± 1.5	$0.002^{a,*}$	0.484
	Rotation ROM	2.4 ± 3.0	$0.026^{a,*}$	2.3 ± 1.6	$<0.001^{a,*}$	0.614

Hip	Flexion	0.9 ± 1.9	0.038[a,*]	0.03 ± 3.5	0.965[a]	0.322
	Extension	0.1 ± 3.0	0.833[b]	0.4 ± 1.8	0.203[a]	0.635
	Abduction	-0.5 ± 1.5	0.176[a]	-0.3 ± 1.1	0.130[a]	0.577
	Adduction	0.7 ± 1.9	0.121[a]	1.3 ± 1.2	<0.001[b,*]	0.144
Knee	Flexion	-0.1 ± 1.3	0.408[b]	1.4 ± 4.5	0.113[a]	0.190
	Extension	1.8 ± 3.1	0.013[a,*]	0.9 ± 4.1	0.280[a]	0.306
	Abduction	0.6 ± 2.4	0.156[b]	2.3 ± 5.1	0.002[b,*]	0.253
	Adduction	-0.2 ± 1.5	0.485[a]	0.7 ± 6.0	0.855[b]	0.510
Ankle	Plantar flexion	-1.7 ± 5.1	0.211[b]	-3.1 ± 6.7	0.022[a,*]	0.628
	Dorsi-flexion	-0.2 ± 2.2	0.858[b]	-1.0 ± 4.7	0.271[a]	0.696
	Inversion	-0.9 ± 5.2	0.418[a]	-0.5 ± 5.5	0.670[a]	0.834
	Eversion	-0.7 ± 8.1	0.697[a]	0.0 ± 5.6	0.992[a]	0.746
	Abduction	-3.6 ± 8.6	0.017[b,*]	-1.3 ± 5.6	0.238[a]	0.357
	Adduction	-1.5 ± 4.8	0.151[a]	0.5 ± 6.7	0.703[a]	0.322

*Table 6.1: Mean differences per group between peak joint angles in unfatigued (pre) and fatigued (post) state. ROM = range of motion. *Significant difference (p<0.05). [a]Normally distributed variable. [b]Not-normally distributed variable.*

A group * exhaustion interaction effect ($p < 0.05$) was found for peak trunk flexion (Table 6.1). In the NOVICE group, trunk flexion increased with 3.0 ± 4.2 degrees with exhaustion, which was significantly more than in the COMP group, in which trunk flexion increased with only 0.2 ± 1.9 degrees.

SPM analysis of the whole stride cycle revealed that NOVICE runners show a decrease in pelvic anterior tilt during a small portion of the swing phase, a decrease in hip flexion during stance phase, increased hip adduction right before and during foot strike, and decreased knee flexion combined with increased plantar flexion during swing phase (figure 6.3). COMP runners showed a similar decrease in pelvic anterior tilt during a small portion of the swing phase, increased pelvic obliquity during stance phase, increased peak hip flexion right after toe-off, increased hip adduction during stance phase, with no changes in the knee and ankle. SPM analysis showed an interaction effect between group and exhaustion for the hip abduction/adduction early in the swing phase: NOVICE runners changed towards more hip abduction, whereas COMP runners changed towards more adduction. No changes in spatiotemporal variables or vertical oscillation were found in both NOVICE and COMP runners.

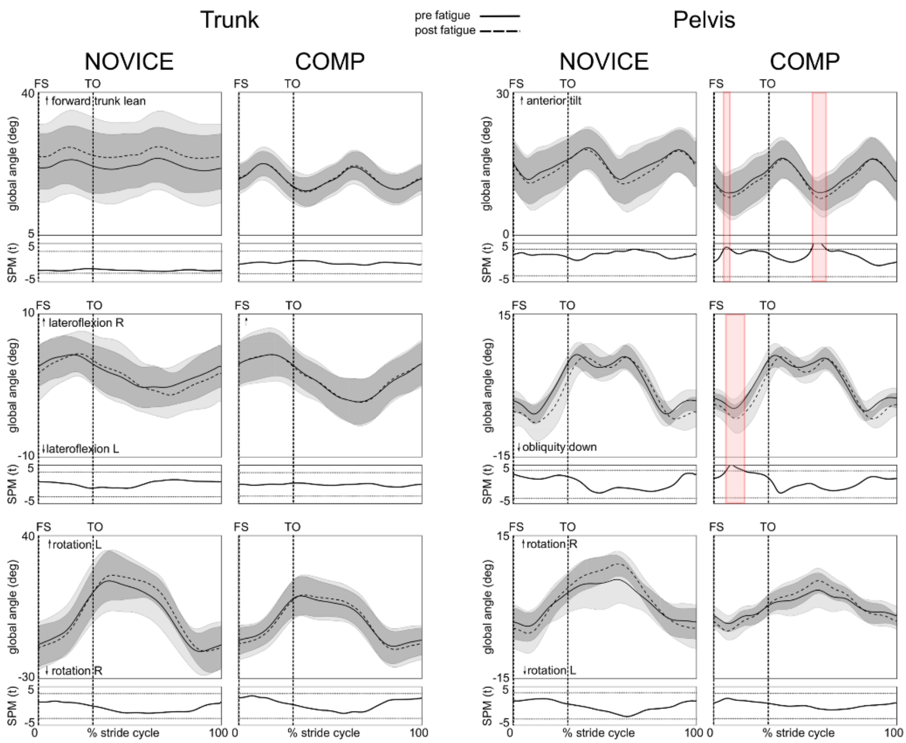


Figure 6.3a: Trunk and pelvis angles at AvS (novice runners, left) 3.33 m/s (competitive runners, right), averaged over stride cycle. Upper panels display joint angles, lower panels display SPM(t) values with the dotted line representing the critical threshold. When the SPM(t) value crosses the critical threshold, there is a significant change (p < 0.05). Red highlighting indicates a fatigue effect. Foot strike (FS) and toe-off (TO) are indicated on the x-axis.

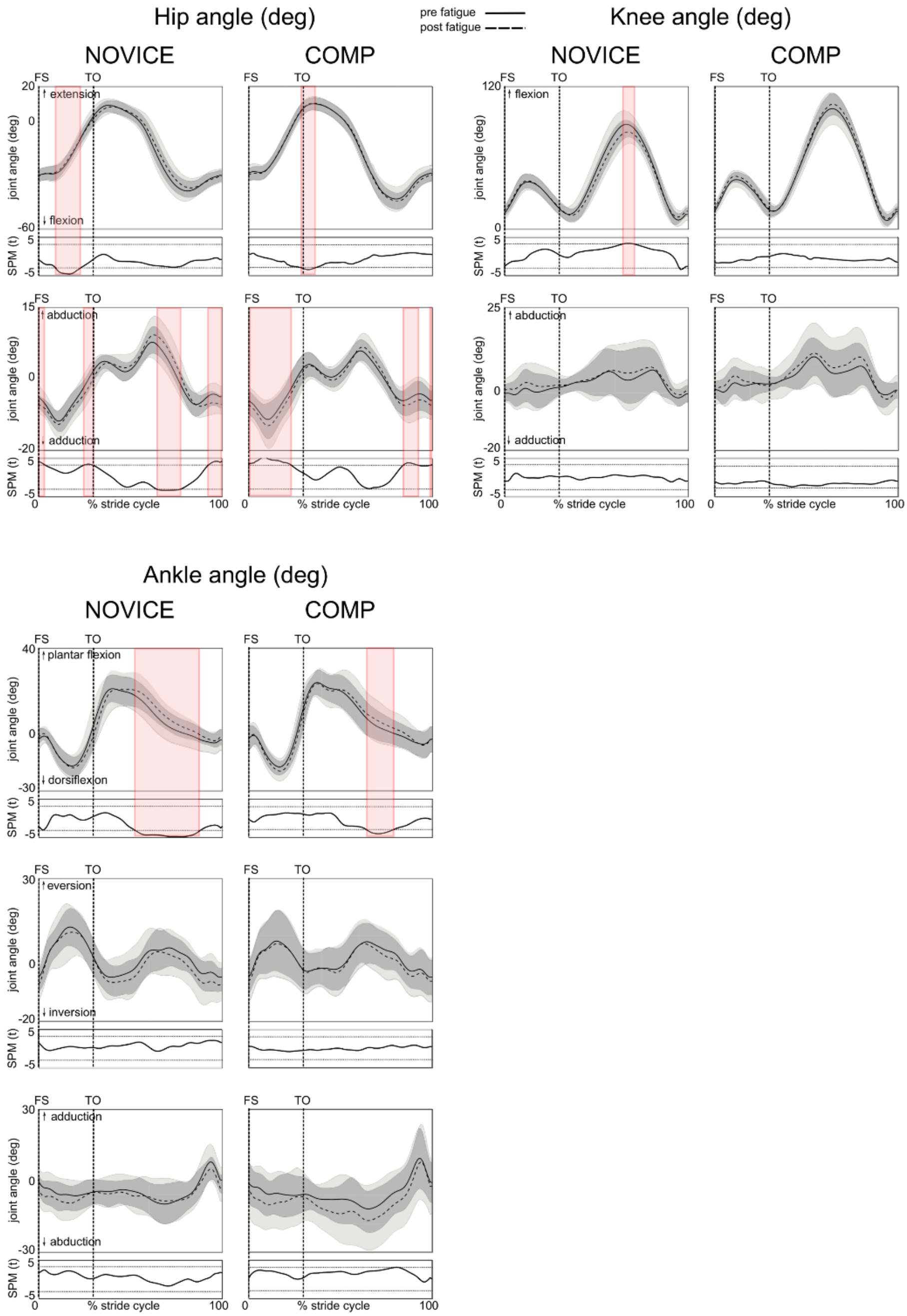


Figure 6.3b: joint angles at AvS (novice runners, left) 3.33 m/s (competitive runners, right), averaged over stride cycle. Upper panels display joint angles, lower panels display SPM(t) values with the dotted line representing the critical threshold. When the SPM(t) value crosses the critical threshold, there is a significant change ($p < 0.05$).

Red highlighting indicates a fatigue effect. Foot strike (FS) and toe-off (TO) are indicated on the x-axis.

DISCUSSION AND IMPLICATIONS

The purpose of the present study was to identify changes in running kinematics after an exhaustive run and to determine if these changes are different in novice versus competitive long distance runners. Analysis of the peak joint angles during stance phase indicated that there are differences in kinematics between running in a exhausted versus a fresh state in both groups. When exhausted, runners from both groups ran with higher peak pelvic anterior tilt, and larger pelvic rotation ROM during stance phase (Table 6.1). To determine whether novice runners respond differently to exhaustion compared with competitive long distance runners, interaction effects for group × exhaustion were calculated. NOVICE runners had a bigger increase in peak forward trunk lean at the end of the exhaustive run, while COMP runners maintained the same trunk position. This increased forward trunk lean with exhaustion in novice runners is in concordance with previous studies[8,17]. Increased trunk flexion has been demonstrated as a result of local fatigue of the trunk musculature[22]. Forward trunk lean during running causes an anterior displacement of the centre of mass, and has been associated with a greater hip extensor moment and a lower knee extensor moment[23]. Although the direction of this association is unknown, this indicates that increased forward trunk lean may also be due to fatigue in the knee extensors.

Analysis of the kinematic waveforms of the whole stride showed increased ankle plantar flexion during swing phase in both groups (Figure 6.3). SPM analysis revealed that there is an interaction effect for group × exhaustion for hip abduction/ adduction at 46-55% of the stride cycle. Novice runners change towards more hip abduction during this part of the swing phase, whereas COMP runners change towards more hip adduction. In both groups, hip abduction/adduction ROM is increased with exhaustion, which is in concordance with the findings of Willson et al.[14] in recreational runners. Since the increase in hip abduction in the NOVICE group was accompanied by an increase in ankle plantar flexion and a decrease in knee flexion (thus a more extended leg), the hip abduction may have been a compensation strategy to keep the foot of the ground while swinging the leg forward. Although the absolute changes are small (1-3 degrees), they indicate a systematic change in running kinematics with exhaustion. This could be explained by fatigue in the trunk, hip and thigh musculature.

As stated in the introduction, some kinematic variables have been associated with the development of overuse injuries. Increased hip and knee internal rotation have been associated with patellofemoral pain[4]. Increased hip internal rotation, hip adduction and knee internal rotation have been associated with iliotibial band syndrome[5,6]. Finally, increased ankle pronation has been associated with lower leg pain[7]. In the present study, hip adduction increased in both groups, which may increase the injury risk with exhaustion. No differences were found in knee adduction and ankle pronation between the fresh and exhausted state in both groups.

Using SPM for analysing the kinematic response to exhaustion allowed us to see differences in the response to exhaustion during running across the entire stride cycle. As can be seen in Figure 6.3, there were more differences within groups than just at the minimum and maximum joint angles. In the hip, knee and ankle, the NOVICE runners show changes in joint angles over a larger portion of the stride compared to COMP runners.

There are some limitations to the current study design. Due to the speed limitation of the instrumented treadmill, we were not able to record kinematics of the COMP runners at a speed equal to their time trial speed. 3.3 m/s is below the average training speed of most of the COMP runners, so it is a less relevant speed for this group. However, having both groups run at comparable speeds allowed for more accurate comparison between groups. COMP runners ran for a shorter period of time than the NOVICE runners. This is partly due to their faster 3200 m time, but also to the ability of the COMP runners to pace their 3200 m run, since they have more experience with running time-trials. However, since the BORG scores of both groups were similar and above 17/20, we are confident that both groups were exhausted after the treadmill run. Finally, the COMP group may include less injury-prone runners than the NOVICE group due to their training history. COMP runners have had years of high volume training experience, which is not possible for people who are prone to develop injuries. Therefore, the COMP runners may be less likely to show biomechanical risk factors for developing injuries.

Novice runners show more changes in running kinematics when exhausted compared with well-trained, competitive runners. For novice runners in particular, injury risk may be higher in an exhausted state. When assessing a runner’s form and/or injury risk, one must keep in mind that measuring kinematic variables in a fresh state may not be reflective of a runner’s form during an actual, exhaustive training session.

CONCLUSION

In conclusion, runners showed changes with exhaustion at the trunk, pelvis, hip and knee level. These changes were more pronounced in novice runners compared with competitive, long distance runners. This may be caused by more muscular fatigue in the trunk, hip and thigh muscles in untrained runners.

REFERENCES

1 Ferber R, Hreljac A, Kendall KD. Suspected mechanisms in the cause of overuse running injuries: a clinical review. *Sports Health* 2009; 1(3):242–246.

2 van Gent RN, Siem D, van Middelkoop M, et al. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br J Sports Med* 2007; 41(8):469–480.

3 Buist I, Bredeweg SW, Bessem B, et al. Incidence and risk factors of running-related injuries during preparation for a 4-mile recreational running event. *Br J Sports Med* 2010; 44(8):598–604.

4 Boling MC, Padua DA, Marshall SW, et al. A prospective investigation of biomechanical risk factors for patellofemoral pain syndrome: the Joint Undertaking to Monitor and Prevent ACL Injury (JUMP-ACL) cohort. *Am J Sports Med* 2009; 37(11):2108–2116.

5 Ferber R, Noehren ATCB, Hamill J, et al. Competitive female runners with a history of iliotibial band syndrome demonstrate atypical hip and knee kinematics. *J Orthop Sport Phys Ther* 2010; 40(2):52–58.

6 Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech* 2007; 22(9):951–956.

7 Willems TM, Witvrouw E, De Cock A, et al. Gait-related risk factors for exercise-related lower-leg pain during shod running. *Med Sci Sports Exerc* 2007; 39(2):330–339.

8 Koblbauer IF, van Schooten KS, Verhagen EA, et al. Kinematic changes during running-induced fatigue and relations with core endurance in novice runners. *J Sci Med Sport* 2014; 17(4):419–424.

9 Dierks TA, Davis IS, Hamill J. The effects of running in an exerted state on lower extremity kinematics and joint timing. *J Biomech* 2010; 43(15):2993–2998.

10 Dierks TA, Manal KT, Hamill J, et al. Lower extremity kinematics in runners with patellofemoral pain during a prolonged run. *Med Sci Sports Exerc* 2011; 43(4):693–700.

11 Clansey AC, Hanlon M, Wallace ES, et al. Effects of fatigue on running mechanics associated with tibial stress fracture risk. *Med Sci Sports Exerc* 2012; 44(10):1917–1923.

12 Derrick TR, Dereu D, Mclean SP. Impacts and kinematic adjustments during an exhaustive run. *Med Sci Sports Exerc* 2002; 34(6):998–1002.

13 Mizrahi J, Verbitsky O, Isakov E. Fatigue-related loading imbalance on the shank in running: a possible factor in stress fractures. *Ann Biomed Eng* 2000; 28(4):463–469.

14 Willson JD, Loss JR, Willy RW, et al. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech* 2015; 48:4155–4159.

15 Bazett-Jones DM, Cobb SC, Huddleston WE, et al. Effect of patellofemoral pain on strength and mechanics after an exhaustive run. *Med Sci Sports Exerc* 2013; 45(7):1331–1339.

16 Abt JP, Sell TC, Chu Y, et al. Running kinematics and shock absorption do not change after brief exhaustive running. *J Strength Cond Res* 2011; 25(6):1479–1485.

17 Strohrmann C, Harms H, Kappeler-Setz C, et al. Monitoring kinematic changes with fatigue in running using body-worn sensors. *IEEE Trans Biomed Eng* 2012; 16(5):983–990.

18 Pataky T, Robinson M, Vanrenterghem J. Vector field statistical analysis of kinematic and force trajectories. *J Biomech* 2013; 46(14):2394–2401.

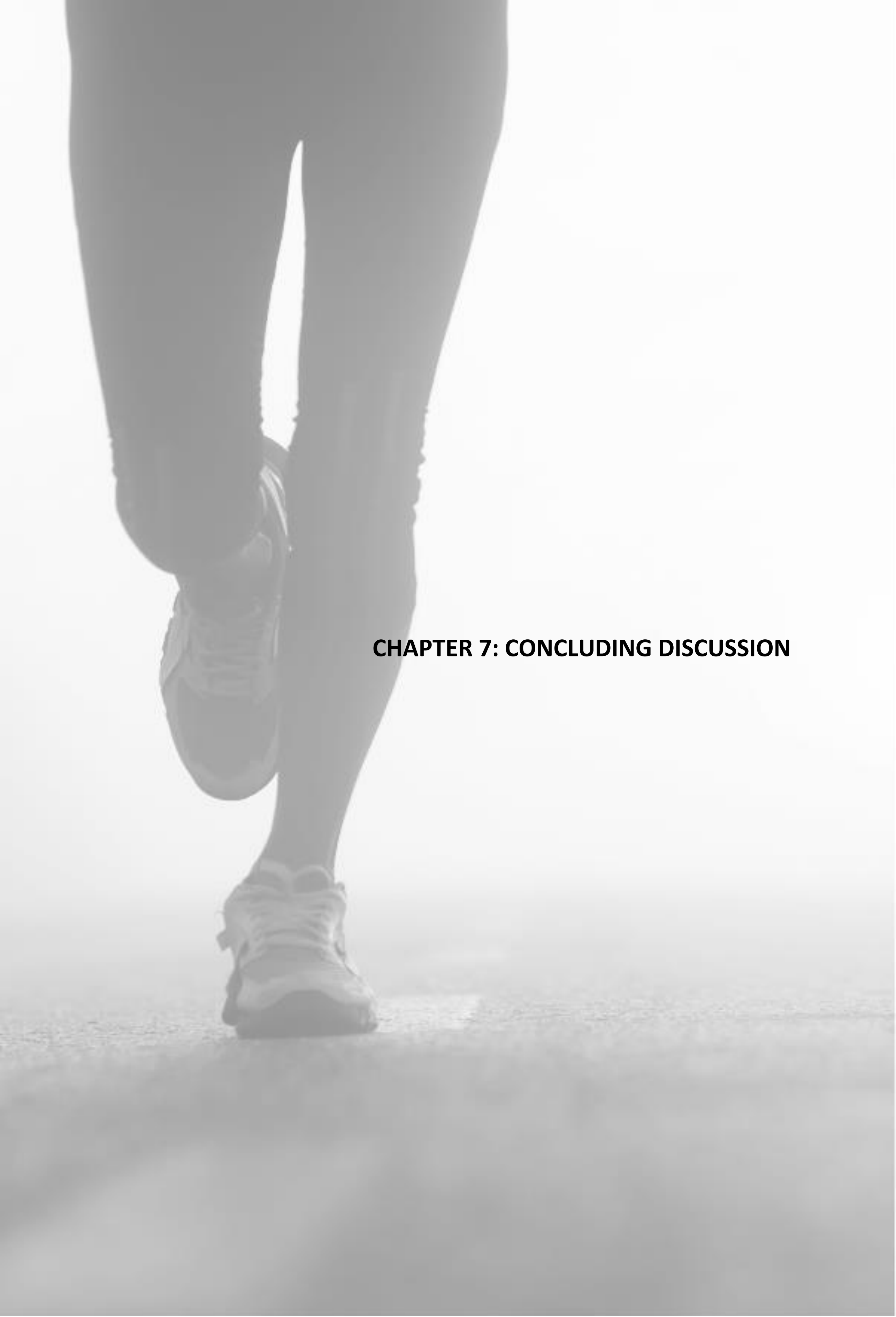
19 Borg G. *Borg's perceived exertion and pain scales*. Champaign, Il., Human Kinetics, 1998.

20 Davis RB, Ounpuu S, Tyburski D, et al. A gait analysis data collection and reduction technique. *Hum Mov Sci* 1991; 10(5):575–587.

21 Pataky T, Vanrenterghem J, Robinson M. Two-way ANOVA for scalar trajectories, with experimental evidence of non-phasic interactions. *J Biomech* 2015; 48(1):186–189.

22 Hart JM, Kerrigan DC, Fritz JM, et al. Jogging kinematics after lumbar paraspinal muscle fatigue. *J Athl Train* 2009; 44(5):475–481.

23 Teng H-L, Powers CM. Influence of trunk posture on lower extremity energetics during running. *Med Sci Sports Exerc* 2015; 47(3):625–630.



CHAPTER 7: CONCLUDING DISCUSSION

OVERVIEW

The main purpose of this doctoral thesis was to determine the influence of a typical 12-week running program for beginners on running kinematics and kinetics, tibial bone geometry and density, and Achilles tendon stiffness in novice runners. This study was motivated by the increased popularity of running programs for beginners over the last decades and thereby the growing number of novice runners. We investigated the effect of a 12-week running program for beginners on three different areas: running kinematics and kinetics (chapter 2), the tibial bone (chapter 3), and the Achilles tendon (chapter 4 and 5). Finally, we examined the effect of both long term training and fatigue on running kinematics and kinetics (chapter 6).

The purpose of this chapter is to discuss the specific and general conclusions of the studies performed for this thesis and their implications to the research field of running biomechanics. Furthermore, general limitations to the study design and execution and their impact on the study results are discussed. Finally, future perspectives on the topic of musculoskeletal loading and adaptation in novice runners are presented.

SPECIFIC CONCLUSIONS/IMPLICATIONS

In **Chapter 2**, we studied changes in running kinematics and kinetics after a 12-week running program for beginners. We know from the literature that well-trained runners have better running economy than novice runners[1] and have a lower injury risk.[2] Therefore, we hypothesized that there is a training effect on running kinematics and kinetics. We investigated whether 12 weeks of training will already influence running kinematics and kinetics.

Hypothesis: after 12 weeks of training, novice runners will adopt running kinematics and kinetics that have been associated with lower injury risk and better running economy.

After 12 weeks of running, participants showed no changes in peak joint angles. Regarding kinetic variables, we found an increase in the peak hip external rotation moment from 0.02 (SD: 0.02) to 0.03 (SD: 0.02) Nm/kg. Also, peak vertical GRF decreased significantly from 23.1 (SD: 1.9) N/kg to 22.2 (SD: 1.8) N/kg.

These results do not confirm the hypothesis that runners progress towards a more economical and less injury-prone running style. Variables that are associated with improved running economy include higher ankle plantar flexion velocity, increased leg stiffness, decreased ground contact time, decreased vertical movement and lower braking forces,[3–6] none of which were found to change with 12 weeks of running training in our sample. Similarly, risk factors for overuse injuries, such as hip adduction, knee internal rotation and ankle pronation during stance, and loading rate[7–9], did not change with training.

In the GRF results, we saw a decrease in peak vertical GRF. Although loading rate is associated with increased injury risk, peak GRF is not. It is therefore unlikely that a reduction in peak vertical GRF will contribute to a lower injury risk. In summary, we can conclude from this study that 12 weeks of running training without any additional instructions, drills or strength training, does not improve running technique.

In **Chapter 3**, we assessed the influence of a 12-week running program for beginners on properties of the tibial bone in female novice runners. Increasing the mechanical loading of bone can cause an increase in bone size and density[10], but it is unclear whether 12 weeks of endurance running provides sufficient bone strains to provoke an osteogenic response.

Hypothesis: Bone density and geometry (total area and cortical area) of the tibia will increase after a 12-week running program for novice runners.

Significant increases in total mass (1.9%) and total area (5.3%) at the distal tibia (4% of tibia length) were found, as well as an increase in cortical density at 38% of the tibia length. These findings indicate early increases in tibia size and density after only 12 weeks of training. Comparison of our results to other studies in the literature on the effect of short term training programs on tibial bone properties show that running is successful in increasing tibial size and density, but not as successful as football training. [11–14] Since running is more feasible than football training because it can be done alone, anywhere and at any time, it may still be an effective intervention to increase bone strength.

Significant correlations were found between loading rate and increase in bone mass at 4%, and between impact peak and change in cortical area at 38%. Therefore, it seems that higher loading of the tibia per step during running is positively related to changes in bone properties, partially confirming our second hypothesis. In conclusion, running seems to cause increases in bone geometry at the distal tibia. Since women are at higher risk of osteoporotic fractures as a consequence of loss in bone mass[15], running could be advised as a good mode of physical activity to use as a preventive strategy for loss of bone mass. However, it must be noted that this study only investigated bone strength at the distal tibia, which is not a very common site for osteoporotic fractures. Given the low number of MTSS cases in our study (4%) and the positive adaptations to the distal tibial bone, it is suggested that the cumulated tibial loading in our running program was well within the loading capacity for the majority of the participants.

In **Chapter 5**, we analysed the changes in Achilles tendon stiffness over the course of a 12-week running program for beginners. Previous studies have shown that Achilles tendon stiffness increases with training and decreases with inactivity.[16–18] However, the specific effect of running on Achilles tendon stiffness is less established. Cross-sectional studies on athletes from different sports suggest that sports involving high tendon loading, such as sprinting and ski jumping, have a positive effect on tendon stiffness.[19,20] Therefore, we aimed to associate Achilles tendon loading with Achilles tendon adaptation by associating ankle moment (which is related to tendon loading) during running with changes in Achilles tendon stiffness.

Hypothesis 1: Achilles tendon stiffness will increase after 12 weeks of running in novice runners.

Hypothesis 2: Ankle plantar flexor moment during running is positively related to changes in Achilles tendon stiffness after a 12-week running program for novice runners.

We found no changes in Achilles tendon stiffness after the 12-week running program. However, we found a significant, positive correlation between ankle moment during running and change in Achilles tendon stiffness, indicating that runners with high ankle moments have slightly larger increases in Achilles tendon stiffness than runners with low ankle moments. From this study, it can be concluded that 12 weeks of running does not cause significant increases in Achilles tendon stiffness. Whether this is due to the short duration of the training program or the lack of high Achilles tendon strains during running remains unclear. However, since strength training programs of similar duration are successful in increasing tendon stiffness[18,21,22], we suggest that the latter is the case. Strength training may therefore be more effective for increasing tendon stiffness than running.

In **Chapter 6**, we compared adjustments in running kinematics during an exhaustive run between novice runners and well-trained, competitive long distance runners. Running kinematics may change as the runner gets fatigued over the course of a strenuous training session. We compared novice runners to well-trained, competitive long distance runners to study the interaction effect between training status and fatigue on running kinematics.

Hypothesis: novice runners show greater changes in kinematics during an exhaustive run compared to well trained, competitive long distance runners.

Both novice and competitive runners adjusted their running kinematics as they got fatigued. Both groups showed an increase in peak pelvic anterior tilt and an increase in pelvic rotation range of motion at the end of the exhaustive run. Novice runners showed more pelvic anterior tilt and rotation at baseline, indicating that competitive runners adapted towards this 'novice' running pattern as they got fatigued. Novice runners also showed a significant increase in forward trunk lean when fatigued, which was not the case in the competitive runners. This study showed that fatigue, developed over the course of an intensive run, leads to changes in running kinematics that may be detrimental for performance. Also, it shows that, when assessing a runner's running technique, measurements in an unfatigued state may not reflect the actual situation during training or competition, since running kinematics change with fatigue. This happens especially in novice runners who are not trained to cope with exhaustion during a run.

GENERAL CONCLUSIONS/IMPLICATIONS

The running program used in this study was intended to cause a progression in mechanical loading per training session by increasing the weekly running distance (from 0 to 5 km or from 5 to 10 km). Overall, this increase in running distance was well tolerated by the participants. Although we did not measure any cardiorespiratory parameters (such as maximal oxygen uptake), it seems safe to conclude that the general fitness level of the participants increased, as they were all able to run for a longer period of time after the running program, even though their running speed did not change. The mechanical loading per training session is not only determined by the running distance (number of steps) but also by the loading per step. By measuring kinematics and kinetics before and after the training program, we wanted to determine if the loading per step changed with training. We hypothesized that loading per step would decrease, since runners may improve their running technique with training. We focused on parameters that were previously related to overuse injuries in the literature, since changes in these variables may indicate changes in loading per step. We however found no changes in kinematics after training, nor were there changes in any of the kinetic parameters previously related to overuse injuries. We can therefore conclude that our running program did not lead to changes in loading per step. This means that the loading per training session, over the course of the running program, increased proportionally with the increase in the number of steps during the run.

Despite the increased loading caused by the running program, we saw only minor adaptations to the tibial bone and no changes to the Achilles tendon. Loading of the tibia was estimated by measuring components of the vertical GRF curve: the mean and instantaneous vertical loading rate and the impact peak, which are all measures of the shocks on the body during the landing phase of running. These shocks are related to loading of the tibia.[23] With the increasing number of steps during the running program comes an increasing number of shocks on the tibia. These forces may cause an osteogenic response, but previous studies have also shown that, when there is not enough rest in between the training sessions, overuse injuries will occur.[24] In our study sample, the number of overuse injuries to the tibia was rather low (only three participants out of the whole group of 71 runners complained of shin pain), indicating a small number of musculoskeletal maladaptations. On the other hand, we did find some early indications for bone adaptation in the female runners. Area and mass of the distal tibia increased significantly in the female participants, indicating that the change in mechanical loading environment caused by the increasing number of running steps leads to adaptations in bone tissue. Running therefore seems to provide high enough bone strains to trigger an osteogenic response. This result supports the suggestion that running training can be beneficial for bone health.

On the other hand, we found no changes in the Achilles tendon stiffness after 12 weeks of running. We used ankle plantar flexor moment during running as an approximation for Achilles tendon loading. As with the bone loading, we can assume that Achilles tendon loading increases proportional with the increase in training distance during the running program, since ankle plantar flexor moment during running did not change with training. However, this loading was not sufficient to result in enough tendon strain to increase Achilles tendon stiffness. The lack of change in Achilles tendon stiffness suggests that either the tendon strains during (relatively slow) running were too low to trigger an adaptation response, or the duration of the running program was insufficient to detect adaptation responses. Several studies have shown that strength training does increase tendon stiffness within a similar time window as our study.[17,25,26] This suggests that the tendon strains during our running program were not sufficient to cause adaptation in tendon size or structure in such a short period. On the other hand, a running program with higher Achilles tendon strains may have led to more Achilles tendon injuries. In order to increase Achilles tendon stiffness, which may be beneficial for running economy[17,27,28], it may be necessary to include additional exercises in the training program. In the literature, various training strategies have been proposed to increase Achilles tendon stiffness, such as plyometric training[29], weight training[21] and isometric strength training.[26] From the combined results, it seems that isometric training at high percentages (90-100%) of MVC is highly effective in increasing Achilles tendon stiffness.[25,26]

The individual running style of a runner will cause a specific loading pattern during each running step having a potential influence on the adaptations to the tibia and the Achilles tendon. Therefore, in this thesis we also investigated if the loading on the tibia and the Achilles tendon during running is related to the change in the mechanical properties of the tibia and Achilles tendon. We were not able to determine directly the loading on the tibia and the Achilles tendon but used, based on the literature, the GRF and the ankle plantar flexor moment as approximations for the musculoskeletal loading. A number of significant correlations between loading variables and mechanical properties were found, indicating that the running pattern of the individual runner will partially determine the amount of adaptation that occurs during the running program. Runners who ran with higher loading rate and ankle plantar flexor moments during running showed larger adaptations in tibial bone mass and Achilles tendon stiffness, respectively. Naturally, these correlations must be interpreted with caution, since this method does not allow for the establishment of causal relationships.

In the final study included in this thesis, we found that running kinematics are influenced by both fatigue and training level, with novice runners being more affected by fatigue than well trained runners. This indicates that especially in novice runners, special attention to the running style should be paid when they feel fatigued as the adaptations might have a negative effect on the musculoskeletal loading. Feedback on running kinematics and kinetics, using coaching, visual feedback[30,31] or auditory feedback[32], may help to maintain a stable running pattern with fatigue. Unfortunately, we did not measure running kinetics in this particular study, which makes it difficult to draw conclusions about the influence of fatigue on loading parameters. However, this study indicates that measuring loading during running in a fresh state may not reflect actual loading during a tough training session, especially in novice runners. For future studies, measuring loading during running in a fatigued state may therefore be considered.

Even though the running program did not cause substantial musculoskeletal adaptations, it did not cause high injury rates. Only 12.7% of participants reported running-related pain. For 8.4% of participants, their injuries were so severe that they had to quit the running program. In comparison to previous training studies in the literature, the injury incidence in the present study is quite low. In a recent training study on 129 novice runners by Baltich et al, 40% of the participants reported a running related injury over the course of a 6 month period, with the majority (79%) of the injuries occurring in the first 8 weeks of training.[33] Since overuse injuries result from an imbalance between loading and loading capacity, we can conclude that, for our running program, loading of the Achilles tendon and tibia was well balanced to the loading capacity (defined by tibial BMD and Achilles tendon stiffness) of the participants, even though this loading capacity did not increase much over the 12 week time period. The majority of participants who quit the running program did so because of lack of time or lack of motivation to run.

LIMITATIONS

The results from the different studies presented in this thesis should be interpreted taking into account several limitations to the study design and methodology. Limitations that apply only to individual chapters are presented in the discussion sections of these chapters. Limitations and considerations that apply to multiple chapters and their possible influences on the conclusions are presented below.

Running program

With any training study, compliance to the training program is important to draw valid conclusions about the effects of the program. We therefore tried to keep participants motivated as much as possible. We organized supervised training sessions and allowed participants to choose from two different training programs to keep the training sessions fun and challenging. Still, 42% of the participants dropped out of the study. 28% dropped out due to lack of motivation or lack of time. Drop-out was higher in the beginner program compared to the more advanced program. In addition to the number of participants that dropped out of the study, a large number of participants did complete the running program, but did not complete all tests. Performing the posttests in two different labs (the pQCT scans were taken at a different lab than the 3-dimensional running analysis and the tendon assessment) proved to be a barrier for compliance. This decreased sample sizes, and therefore the power of our studies. The majority of the participants were students, who may have been more likely to drop out due to exam periods during the course of the study.

Choice of variables

Because of practical reasons, we chose to measure loading variables such as IP, LR and ankle plantar flexion moment as approximations for tibia loading and Achilles tendon loading. However, IP and LR reflect loading of the whole body, not of the tibia. Therefore, perhaps more direct approximations can be used. Using musculoskeletal modelling, joint and muscle forces during running can be computed. With finite element analysis, strain and stress of the tibia and Achilles tendon can be computed. Still, these estimations of stress and strain are based on musculoskeletal models which are simplified representations of the actual muscle coordination. Given the limitations of these techniques, the strain and stress values will still be an estimate for the actual loading of the structures, but they may be closer than the variables used in this thesis. However, these techniques are time-consuming and currently not practical for large samples.

Lab measurements

The measurement of running kinematics and kinetics in the movement lab comes with limitations. Apart from the fatigue protocol, in which we used an instrumented treadmill, we measured running kinematics and kinetics while running across a 12 m runway in the movement lab. The laboratory setting, including all the markers attached to the skin, together with the almost constant acceleration and deceleration on the short runway, may lead to unnatural running behaviour. Runners were instructed to run at a self-selected, comfortable running speed, but because of the relative short runway, this may have deviated from their actual training speed. Furthermore, all subjects wore standardized, neutral running shoes during the measurements. This allowed for the use of foot markers directly on the foot, protruding through holes in the shoes, but the shoes may have had different properties than their regular running shoes, which they wore during the training sessions. This difference in shoes may have affected their running kinematics and kinetics.

Some researchers choose to use a treadmill for indoor lab measurements, which has the advantage that subjects can run at a constant speed. Also, multiple consecutive steps can be analysed using a treadmill, since the treadmill is always in view of the camera’s, whereas the subject runs in and out of camera view when running overground. However, Willy et al. found that treadmill running resulted in 12.5 % greater peak Achilles tendon force.[34] Using a treadmill would therefore probably have led to an overestimation of Achilles tendon loading during running.

Monitoring of training activity

In order to monitor the training activities of the participants, the runners kept a log book in which they noted their training distance and time. Since this method is based on self-report, participants may have over- or under-reported their training activities. In addition, we did not monitor training activity outside of the training hours. Participants were instructed to refrain from additional running and jumping exercise besides the running program, but this was not checked. Supplying participants with activity trackers or accelerometers could potentially solve this problem, assuming that these are worn at all times.

Statistics

In Chapter 2, analysis of the dependent variables was limited to peak values for joint angles, moments and GRF, because these values have been related to injury risk and running economy in the literature. In chapter 6, SPM was used because of the explorative character of this study. SPM has the advantage that it is able to detect differences in the whole timeline of the joint angle, joint moment or GRF instead of just the peak values. This enables the detection of time shifts between variables.

For Chapters 3, 5 and 6, both legs of each subject were included in the analysis in order to maximize the number of data points available. However, legs were entered into the analysis independently. The rationale behind this choice was that, although two legs belong to the same participant, loading and adaptation can vary considerably. Different loading during running and different adaptational responses explain why injuries frequently occur unilaterally. However, the left and the right leg of one subject are obviously related through common properties such as body weight, height and behavioural characteristics, which can argue in favour of paired testing.

DIRECTIONS FOR FUTURE RESEARCH

The findings of the four studies included in this doctoral thesis have raised several questions that cannot be answered with the collected data and could form the basis for future research.

First, while we studied musculoskeletal adaptations after a running program, the focus of many studies on novice runners is on maladaptations and, consequently, injury. These maladaptations occur when the repeated musculoskeletal loading during a training program exceeds the loading capacity. In order to study risk factors for developing overuse injuries, a prospective study design must be used, wherein runners who develop overuse injuries are compared to runners who remain healthy while following the same running program. However, the present sample sizes did not allow for studying injury risk factors. In a recent study by Nielsen et al. that followed 933 novice runners for a year, 15% of the participants in the study suffered from MTSS and 7% developed Achilles tendinopathy.[35] In order to obtain a subsample of 11 Achilles tendinopathy patients and 16 MTSS patients, as prescribed by our sample size calculations, one would need a total sample of 157 and 107 subjects, respectively, to follow for a year. This sample then has to be inflated substantially to account for the high drop-out rates associated with this type of training study. All in all, studying injury risk factors in novice runners measuring the same parameters used in the present study would become a very large project.

Although this PhD study has shown that a commonly used 12 week running program only shows limited musculoskeletal adaptations, it is not clear whether the training duration or the training intensity limited musculoskeletal adaptations. Therefore, it would be interesting to follow the novice runners for a longer period of time to see how Achilles tendon stiffness and tibial geometry and density develop. For adaptations of the Achilles tendon mechanical properties, it is unclear how long the study duration should be. Several studies have found relatively quick adaptations with strength training[18,21,22], but running studies have failed to find adaptations in tendon stiffness, even after 9 months.[36] To answer the question whether different loading patterns cause different musculoskeletal adaptations, it would also be interesting to include a sample of midfoot and forefoot strikers, since they experience higher Achilles tendon forces.[37,38] In our sample, this comparison was not possible since only a very small proportion (less than 1 percent) of novice runners runs with a forefoot strike pattern.[39]

Future studies should aim to calculate loading magnitude more accurately. As mentioned in the introduction, loading consists of the loading per step multiplied by the number of steps. Cumulative loading must therefore be calculated by multiplying the loading per step parameter, such as loading rate, by the number of steps taken in a training session. However, in order to quantify tissue loading more accurately, any physical activity outside of the training sessions should also be monitored. This can be achieved by supplying the participants with activity trackers or accelerometers. Accurately quantifying cumulative tissue loading over the course of the training study would give more insight in the relationship between tissue loading and adaptation.

When measuring Achilles tendon stiffness, we considered the Achilles tendon as one entity, measuring the elongation of the free tendon at the musculoskeletal junction of the gastrocnemius medialis. Actually, the Achilles tendon consists of three distinct subtendons. Loading of the Achilles tendon is heterogeneous: activation of the three different plantar flexors (the soleus, gastrocnemius medialis and gastrocnemius lateralis) will result in separate loading and adaptation of the three subtendons.[40–42] Currently, it is difficult to measure stress and elongation of the three different subtendons in vivo in a dynamic situation. However, this is an active research field, and in the near future it may be possible to study the influence of running on the mechanical properties of the different subtendons of the Achilles tendon separately.

REFERENCES

1 Morgan D., Bransford DR, Costill DL, et al. Variation in the aerobic demand of running among trained and untrained subjects. *Med Sci Sport Exerc* 1995; 27(3):404–409.

2 Videbaek S, Bueno AM, Nielsen RO, et al. Incidence of Running-Related Injuries Per 1000 h of running in Different Types of Runners: A Systematic Review and Meta-Analysis. *Sport Med* 2015; 45:1017–1026.

3 Støren Ø, Helgerud J, Hoff J. Running stride peak forces inversely determine running economy in elite runners. *J Strength Cond Res* 2011; 25(1):117–123.

4 Williams KR, Cavanagh PR. Biomechanical correlates with running economy in elite distance runners. *Proc. North Am. Congr. Biomech.* 1986. p. 287–288.

5 Butler RJ, Crowell HP, Davis IM. Lower extremity stiffness: Implications for performance and injury. *Clin Biomech* 2003; 18:511–517.

6 Nummela A, Keränen T, Mikkelsson LO. Factors related to top running speed and economy. *Int J Sports Med* 2007; 28:655–661.

7 Noehren B, Davis I, Hamill J. ASB clinical biomechanics award winner 2006 prospective study of the biomechanical factors associated with iliotibial band syndrome. *Clin Biomech* 2007; 22:951–956.

8 Willems TM, Witvrouw E, De Cock A, et al. Gait-related risk factors for exercise-related lower-leg pain during shod running. *Med Sci Sports Exerc* 2007; 39(2):330–339.

9 Zadpoor AA, Nikooyan AA. The relationship between lower-extremity stress fractures and the ground reaction force: A systematic review. *Clin Biomech* 2011; 26:23–28.

10 Guadalupe-Grau A, Fuentes T, Guerra B, et al. Exercise and bone mass in adults. *Sport Med* 2009; 39(6):439–468.

11 Helge EW, Aagaard P, Jakobsen MD, et al. Recreational football training decreases risk factors for bone fractures in untrained premenopausal women. *Scand J Med Sci Sports* 2010; 20 Suppl 1:31–39.

12 Lester ME, Urso ML, Evans RK, et al. Influence of exercise mode and osteogenic index on bone biomarker responses during short-term physical training. *Bone* 2009; 45:768–776.

13 Evans RK, Negus CH, Centi AJ, et al. Peripheral QCT sector analysis reveals early exercise-induced increases in tibial bone mineral density. *J Musculoskelet Neuronal Interact* 2012; 12(3):155–164.

14 Ballard TLP, Specker BL, Binkley TL, et al. Effect of protein supplementation during a 6-month strength and conditioning program on areal and volumetric bone parameters. *Bone* 2006;

38(6):898–904.

15 Johnell O, Kanis JA. An estimate of the worldwide prevalence and disability associated with osteoporotic fractures. *Osteoporos Int* 2006; 17:1726–1733.

16 Reeves ND, Maganaris CN, Ferretti G, et al. Influence of 90-day simulated microgravity on human tendon mechanical properties and the effect of resistive countermeasures. *J Appl Physiol* 2005; 98:2278–2286.

17 Albracht K, Arampatzis A. Exercise-induced changes in triceps surae tendon stiffness and muscle strength affect running economy in humans. *Eur J Appl Physiol* 2013; 113(6):1605–1615.

18 Kubo K, Kanehisa H, Fukunaga T. Effects of resistance and stretching training programmes on the viscoelastic properties of human tendon structures in vivo. *J Physiol* 2002; 538(1):219–226.

19 Wiesinger HP, Rieder F, Kösters A, et al. Are Sport-Specific Profiles of Tendon Stiffness and Cross-Sectional Area Determined by Structural or Functional Integrity? *PLoS One* 2016; 11(6):1–16.

20 Arampatzis A, Karamanidis K, Morey-Klapsing G, et al. Mechanical properties of the triceps surae tendon and aponeurosis in relation to intensity of sport activity. *J Biomech* 2007; 40:1946–1952.

21 Kubo K, Morimoto M, Komuro T, et al. Effects of plyometric and weight training on muscle-tendon complex and jump performance. *Med Sci Sports Exerc* 2007; 39(10):1801–1810.

22 Kubo K, Ikebukuro T, Maki A, et al. Time course of changes in the human Achilles tendon properties and metabolism during training and detraining in vivo. *Eur J Appl Physiol* 2012; 112:2679–2691.

23 Judex S, Carlson KJ. Is bone’s response to mechanical signals dominated by muscle forces? *Med Sci Sports Exerc* 2009; 41(11):2037–2043.

24 Warden SJ, Burr DB, Brukner PD. Stress fractures: pathophysiology, epidemiology, and risk factors. *Curr Osteoporos Rep* 2006; 4(3):103–109.

25 Arampatzis A, Karamanidis K, Albracht K. Adaptational responses of the human Achilles tendon by modulation of the applied cyclic strain magnitude. *J Exp Biol* 2007; 210:2743–2753.

26 Burgess KE, Connick MJ, Graham-Smith P, et al. Plyometric vs. isometric training influences on tendon properties and muscle output. *J Strength Cond Res* 2007; 21(3):986–989.

27 Fletcher JR, Esau SP, MacIntosh BR. Changes in tendon stiffness and running economy in highly trained distance runners. *Eur J Appl Physiol* 2010; 110:1037–1046.

28 Arampatzis A, De Monte G, Karamanidis K, et al. Influence of the muscle-tendon unit’s mechanical and morphological properties on running economy. *J Exp Biol* 2006; 209:3345–3357.

29 Fouré A, Nordez A, Cornu C. Effects of plyometric training on passive stiffness of gastrocnemii muscles and Achilles tendon. *Eur J Appl Physiol* 2012; 112:2849–2857.

30 Chan ZYS, Zhang JH, Au IPH, et al. Gait Retraining for the Reduction of Injury Occurrence in Novice Distance Runners: 1-Year Follow-up of a Randomized Controlled Trial. *Am J Sports Med* 2017:1–8.

31 Crowell HP, Davis IS. Gait retraining to reduce lower extremity loading in runners. *Clin Biomech* 2011; 26(1):78–83.

32 Phan X, Grisbrook TL, Wernli K, et al. Running quietly reduces ground reaction force and vertical loading rate and alters foot strike technique. *J Sports Sci* 2016; 35(16):1636–1642.

33 Baltich J, Emery CA, Whittaker JL, et al. Running injuries in novice runners enrolled in different training interventions: a pilot randomized controlled trial. *Scand J Med Sci Sports* 2017;

27:1372–1383.

34 Willy RW, Halsey L, Hayek A, et al. Patellofemoral Joint and Achilles Tendon Loads During Overground and Treadmill Running. *J Orthop Sports Phys Ther* 2016; 46(8):664–672.

35 Nielsen RO, Rønnow L, Rasmussen S, et al. A prospective study on time to recovery in 254 injured novice runners. *PLoS One* 2014; 9(6).

36 Hansen P, Aagaard P, Kjaer M, et al. Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. *J Appl Physiol* 2003; 95:2375–2380.

37 Almonroeder T, Willson JD, Kernozek TW. The effect of foot strike pattern on achilles tendon load during running. *Ann Biomed Eng* 2013; 41(8):1758–1766.

38 Lyght M, Nockerts M, Kernozek TW, et al. Effects of Foot Strike and Step Frequency on Achilles Tendon Stress During Running. *J Appl Biomech* 2016; 32:365–372.

39 Bertelsen ML, Jensen JF, Nielsen MH, et al. Footstrike patterns among novice runners wearing a conventional, neutral running shoe. *Gait Posture* 2013; 38:354–356.

40 Farris DJ, Trewartha G, McGuigan MP, et al. Differential strain patterns of the human Achilles tendon determined in vivo with freehand three-dimensional ultrasound imaging. *J Exp Biol* 2013; 216(4):594–600.

41 Finni T, Hodgson JA, Lai AM, et al. Nonuniform strain of human soleus aponeurosis-tendon complex during submaximal voluntary contractions in vivo. *J Appl Physiol* 2003; 95:829–837.

42 Magnusson SP, Hansen P, Aagaard P, et al. Differential strain patterns of the human gastrocnemius aponeurosis and free tendon, in vivo. *Acta Physiol Scand* 2003; 177:185–195.

APPENDIX I: APPOSITIONS

APPOSITION 1

A movement lab is an artificial environment. It facilitates accurate motion analysis, but it also affects the running movement of the subjects. Recent technological developments allow for more and more possibilities to measure human movement outside the lab.

BIJSTELLING 1

Een bewegingslaboratorium is een kunstmatige omgeving. Het maakt het mogelijk om nauwkeurige bewegingsanalyses uit te voeren, maar het kan ook de loopbeweging van de proefpersoon beïnvloeden. Nieuwe meettechnieken geven steeds meer mogelijkheden om menselijke beweging buiten het laboratorium, in de natuurlijke omgeving te meten.

APPOSITION 2

Running is associated with high injury rates. Still, the health benefits of running outweigh the discomfort and costs associated with injuries.

BIJSTELLING 2

Hardlopen gaat gepaard met een grote kans op blessures. Desondanks wegen de gezondheidsvoordelen van hardlopen op tegen het ongemak en de bijkomende kosten van blessures.

APPOSITION 3

Exercising with peers does not only improve social cohesion, but also increases motivation to exercise, decreases drop-out of the training program and helps with achieving athletic goals.

BIJSTELLING 3

Sporten in groepsverband verbetert de sociale cohesie, bevordert de motivatie om te sporten, vermindert drop-out van het trainingsprogramma en helpt met het bereiken van sportieve doelen.

APPENDIX II: RUNNING PROGRAMS

PROGRAM 1: 0-30 MIN

Week	Session 1	Session 2	Session 3
1	5x (1 min run, 1 min walk)	7x (1 min run, 1 min walk)	10x (1 min run, 1 min walk)
2	12x (1 min run, 1 min walk)	3x (1 min run, 1 min walk) 3x (2 min run, 1 min walk) 3x (1 min run, 1 min walk)	2x (1 min run, 1 min walk) 2x (2 min run, 1 min walk) 1x (1 min run, 1 min walk) 3x (2 min run, 1 min walk)
3	2x (1 min run, 1 min walk) 5x (2 min run, 1 min walk) 2x (1 min run, 1 min walk)	3x (3 min run, 1 min walk) 3x (2 min run, 1 min walk) 3x (1 min run, 1 min walk)	2x (3 min run, 1 min walk) 1x (5 min run, 1 min walk) 2x (2 min run, 1 min walk)
4	1x (3 min run, 1 min walk) 1x (4 min run, 1 min walk) 1x (3 min run, 1 min walk) 1x (4 min run, 1 min walk)	1x (2 min run, 1 min walk) 1x (6 min run, 1 min walk) 1x (2 min run, 1 min walk) 1x (6 min run, 1 min walk)	3x (5 min run, 1 min walk)
5	1x (5 min run, 1 min walk) 1x (7 min run, 1 min walk) 1x (5 min run, 1 min walk)	3x (6 min run, 1 min walk)	2x (8 min run, 1 min walk)
6	1x (5 min run, 1 min walk) 1x (10 min run, 1 min walk) 1x (5 min run, 1 min walk)	1x (6 min run, 1 min walk) 1x (12 min run, 1 min walk) 1x (4 min run, 1 min walk)	1x (7 min run, 1 min walk) 1x (9 min run, 1 min walk) 1x (7 min run, 1 min walk)
7	3x (8 min run, 1 min walk)	1x (15 min run, 1 min walk)	2x (12 min run, 1 min walk)
8	1x (18 min run, 1 min walk)	1x (6 min run, 1 min walk) 1x (12 min run, 1 min walk) 1x (6 min run, 1 min walk)	1x (5 min run, 1 min walk) 1x (9 min run, 1 min walk) 1x (13 min run, 1 min walk)
9	1x (21 min run, 1 min walk)	2x (7 min run, 1 min walk) 1x (14 min run, 1 min walk)	1x (5 min run, 1 min walk) 1x (10 min run, 1 min walk) 1x (5 min run, 1 min walk) 1x (10 min run, 1 min walk)
10	1x (24 min run, 1 min walk)	1x (18 min run, 1 min walk) 1x (6 min run, 1 min walk) 1x (3 min run, 1 min walk)	1x (20 min run, 1 min walk) 1x (5 min run, 1 min walk) 1x (5 min run, 1 min walk)

11	1x (27 min run, 1 min walk)	1x (20 min run, 1 min walk)	2x (15 min run, 1 min walk)
12	1x (30 min run)		

PROGRAM 2: 10-45 MIN

Week	Session 1	Session 2	Session 3
1	1x (5 min jog, 1 min walk) 1x (10 min jog, 1 min walk) 1x (5 min jog, 1 min walk)	1x (6 min jog, 1 min walk) 1x (12 min jog, 1 min walk) 1x (4 min jog, 1 min walk)	1x (7 min jog, 1 min walk) 1x (9 min jog, 1min walk) 1x (7 min jog, 1 min walk)
2	3 x (8 min run, 1min walk)	1x (15 min run, 1 min walk)	2 x (12 min run, 1min walk)
3	1x (18 min run, 1 min walk)	1x (6 min run, 1 min walk) 1x (12 min run, 1 min walk) 1x (6 min run, 1 min walk)	1x (5 min run, 1 min walk) 1x (9 min run, 1 min walk) 1x (13 min run, 1 min walk)
4	1x (21 min run, 1 min walk)	2x (7 min run, 1 min walk, 14 min run, 1 min walk)	2x (5 min run, 1 min walk, 10 min run, 1 min walk)
5	1x (24 min run, 1 min walk)	1x (18 min run, 1 min walk, 6 min run, 1 min walk, 3 min run, 1 min walk)	1x (20 min run, 1 min walk) 1x (5 min run, 1 min walk) 1x (5 min run, 1 min walk)
6	1x (27 min run, 1 min walk)	1x (20 min run, 1 min walk)	2x (15min run, 1 min walk)
7	1x (30 min run, 1 min walk)	1x (20 min run, 1 min walk)	1x (25 min run, 1 min walk)
8	1x (10 min run, 1 min walk) 1x (15 min run, 1 min walk) 1x (10 min run, 1 min walk)	1x (34 min run, 1 min walk)	1x (30 min run, 1 min walk)

9	3x (13min run, 1min walk)	- 1x (35 min run, 1 min walk)	1x (25 min run, 1 min walk, 10 min run, 1 min walk)
10	1x (38 min run, 1 min walk)	2x (20 min run, 1 min walk)	3x (15min run, 1 min walk)
11	1x (40 min run, 1 min walk)	1x (30 min run, 1 min walk)	1x (15 min run, 1 min walk)
12	1x (45 min run, 1 min walk)		

APPENDIX III: SUBJECT LOG BOOK

Dagboek start-to-run			
Naam:			
Proefpersoonnummer:			
	Week 1	**Week 2**	**Week 3**
Datum			
Aantal trainingen			
Gemiddelde duur van de trainingen (minuten)			
Gemiddelde afstand per training (km)			
Blessures/pijnklachten? (ja/nee)			
Zo ja, waar?			
Komen de klachten door het lopen? (ja/nee)			
Lopen moeten staken door pijnklachten? (ja/nee)			
	Week 4	**Week 5**	**Week 6**
Datum			
Aantal trainingen			
Gemiddelde duur van de trainingen (minuten)			
Gemiddelde afstand per training (km)			
Blessures/pijnklachten? (ja/nee)			
Zo ja, waar?			
Komen de klachten door het lopen? (ja/nee)			
Lopen moeten staken door pijnklachten? (ja/nee)			
	Week 7	**Week 8**	**Week 9**
Datum			
Aantal trainingen			
Gemiddelde duur van de trainingen (minuten)			
Gemiddelde afstand per training (km)			
Blessures/pijnklachten? (ja/nee)			
Zo ja, waar?			
Komen de klachten door het lopen? (ja/nee)			
Lopen moeten staken door pijnklachten? (ja/nee)			
	Week 10	**Week 11**	**Week 12**
Datum			
Aantal trainingen			
Gemiddelde duur van de trainingen (minuten)			
Gemiddelde afstand per training (km)			
Blessures/pijnklachten? (ja/nee)			
Zo ja, waar?			
Komen de klachten door het lopen? (ja/nee)			
Lopen moeten staken door pijnklachten? (ja/nee)			

APPENDIX IV: MARKER SET USED FOR THE THREE-DIMENSIONAL RUNNING ANALYSIS

Marker name	Anatomical landmark
LASI	left ASIS
RASI	right ASIS
LPSI	left PSIS
RPSI	right PSIS
LSHO	left shoulder, lateral edge of acromion
RSHO	right shoulder, lateral edge of acromion
CLAV	Clavicular (in between claviculae)
C7	C7
STRN	Sternum (inferior edge)
T10	Thoracic vertebrae 10
RELB	right elbow (lateral epicondyle)
RWRL	right wrist lateral
RWRM	right wrist medial
LELB	left elbow (lateral epicondyle)
LWRL	left wrist lateral
LWRM	left wrist medial
LKNE	left knee lateral
LTHI	left thigh (cluster)
LTHIA	left thigh anterior (cluster)
LTHIP	left thigh posterior (cluster)
LKNEM	left knee medial (static trial only)
LANK	left ankle (lateral malleolus)
LTIB	left tibia (cluster)
LTIBA	left tibia anterior (cluster)
LTIBP	left tibia posterior (cluster)
LANKM	left ankle (medial malleolus, static trial only)
LMTP1	left MTP1 joint (wand)
LNAV	Left navicular bone (wand)
LMTP5	left MTP5 joint (wand)
LHEE	left heel (cluster)
LHEEM	left heel medial (cluster)
LHEEL	left heel lateral (cluster)
LTOE	left big toe (wand)

RKNE	right knee lateral
RTHI	right thigh (cluster)
RTHIA	right thigh anterior (cluster)
RTHIP	right thigh posterior (cluster)
RKNEM	right knee medial (static trial only)
RANK	right ankle (lateral malleolus)
RTIB	right tibia (cluster)
RTIBA	right tibia anterior (cluster)
RTIBP	right tibia posterior (cluster)
RANKM	right ankle (medial malleolus, static trial only)
RMTP1	right MTP 1 joint (wand)
RNAV	right os naviculare (wand)
RMTP5	right MTP 5 joint (wand)
RHEE	right heel (cluster)
RHEEM	right heel medial (cluster)
RHEEL	right heel lateral(cluster)
RTOE	right big toe (wand)

APPENDIX V: CURRICULUM VITAE ELLEN MAAS

2012-2016: **KU LEUVEN**

Leuven, Belgium

PhD researcher at the department of Kinesiology, Human Movement Biomechanics research group.

2011-2012: **ACADEMISCH MEDISCH CENTRUM**

Amsterdam, the Netherlands

Research assistant at the Children's Rehabilitation department.

2010-2011: **ACADEMISCH CENTRUM TANDHEELKUNDE AMSTERDAM**

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Research assistant at the Periodontology department.

2004-2010: **BACHELOR + MASTER HUMAN MOVEMENT SCIENCES, VRIJE UNIVERSITEIT**

Amsterdam, the Netherlands

Specialisation: Sport and Health

Master thesis: 'Estimation of critical torque during intermittent isometric knee extensions in men with diverse fitness levels'. Supervisor: Jo de Ruiter

2003-2004: **1ST YEAR BACHELOR BIOLOGY, THE OHIO STATE UNIVERSITY**

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PUBLICATIONS

Original research papers:

Maas, E., De Bie, J., Vanfleteren, R., Hoogkamer, W., Vanwanseele, B. (2017). Novice runners show greater changes in kinematics with fatigue compared with competitive runners. *Sports Biomechanics*, accepted for publication.

Maas, E.; Jonkers, I.; Peers, K.; Vanwanseele, B. (2013). Achilles tendon adaptation and Achilles tendinopathy in running. Open Access Orthopaedics. Vol. 1, issue 3, p25-30.

Schutte, K.; **Maas, E**.; Exadaktylos, V., Vanwanseele, B. (2015). Wireless tri-axial trunk accelerometry detects deviations in dynamic center of mass motion duet o running-induced fatigue. PloS One 10 (10).

Abstracts, presented at international conferences:

Maas E., Vanwanseele B. (2016). Changes in running kinematics and kinetics after a 12-week running program for beginners. ECSS Congress. Vienna, Austria, 6-9 July 2016.

Schütte K., **Maas E**., Venter R., Berckmans D., Vanwanseele B. (2015). Identifying treadmill running fatigue using trunk accelerometry based measures. International Society of Biomechanics Congress. Glasgow, Scotland, 12-15 July 2015.

Maas E., de Bie J., Vanfleteren R., Hoogkamer W., Vanwanseele B. (2015). Fatigue leads to more changes in trunk and hip kinematics in novice versus competitive runners. ISB. Glasgow, 12-15 july 2015.

APPENDIX VI: ACKNOWLEDGEMENTS, PERSONAL CONTRIBUTION AND CONFLICT OF INTEREST STATEMENTS

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The author, Ellen Maas, has contributed to every part of this project, including the design of the studies, data collection, data processing, data analysis and writing of all papers. The author wrote this manuscript and created the figures (apart from the figures copied with permission).

The author and co-authors declare that they have no conflict of interest.

APPENDIX VII: ACKNOWLEDGEMENTS – DANKWOORD

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APPENDIX VIII: ABBREVIATIONS

3D	Three-dimensional
ANOVA	Analysis of variance
ASIS	Anterior superior iliac spine
AT	Achilles tendon
AvS	Average speed
BMD	Bone mineral density
C7	7th cervical vertebra
COMP	Competitive runner
CS	Cross-sectional
CSA	Cross-sectional area
CT	Computed tomography
DEXA	Dual-energy X-ray absorptiometry
F_{AT}	Achilles tendon force
F_{cable}	Cable force
FS	Foot strike
FFS	Forefoot strike
GRF	Ground reaction force
GRFv	Vertical ground reaction force
HJC	Hip joint center
IP	Impact peak
IVLR	Instantaneous vertical loading rate
KJC	Knee joint center
LD	Long distance
LR	Loading rate
MA_{ext}	External moment arm
MA_{int}	Internal moment arm
MRI	Magnetic resonance imaging
MTJ	Musculotendinal junction
MTP	Metatarsophalangeal joint
MTP1	1st metatarsophalangeal joint
MTP5	5th metatarsophalangeal joint
MTSS	Medial tibial stress syndrome
MTU	Muscle tendon unit
MVC	Maximal voluntary contraction
NOVICE	Novice runner
pQCT	Peripheral quantitative computed tomography

PSIS	Posterior superior iliac spine
RE	Running economy
RFS	Rearfoot strike
ROM	Range of motion
SD	Standard deviation
SPM	Statistical parametric mapping
STJC	Subtalar joint center
T10	10th thoracical vertebra
TCJC	Talocrural joint center
TO	Toe-off
VO2-max	Maximal oxygen uptake